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A COMPONENTIAL ANALYSIS OF CHANGES IN HUMAN INFORMATION PROCESSING
DURING THE DEVELOPMENT OF AUTOMATICITY

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Abstract

This report is concerned with the changes in human information processing which occur with practice. We are addressing the issue of what mechanisms underly the development of automaticity and the manner in which these changes manifested in the human information processing system. The approach taken is to decompose each task into its processing components and evaluate how these change with practice. Three experiments are included in the proposal. Experiment 1 examines the changes in information processing when two tasks -- a memory search task and a recognition running memory task are performed concurrently. The focus of experiment 1 was to determine if automatic processing requires attentional resources. To address this issue, the processing priority was varied between the two tasks. Concurrent measures of RT, A', P300 amplitude, P300 latency and a ratio of RT to P300 were used to assess the attentional requirements of both controlled and automatic processing.

Experiment 2 examines the time-course of the development of automaticity when two tasks -- a memory search task and a pursuit step-tracking task are performed both separately and concurrently. These two tasks do not overlap in their demands for central processing resources. The focus of experiment 2 was to examine the development of automaticity of the different components underlying the memory search task. A fine-grained decomposition of the changes in information processing was accomplished through the joint use of additive factors logic and the P300 component of the event-related brain potential. This localization of improvement in performance with practice can provide important information on the changes accompanying the acquisition of a skill.

Experiment 3 contrasts two theories of automaticity -- process-based and memory-based. Process-based theories assume that the cognitive operations underlying a process become more efficient with practice; however, aside from becoming more efficient, the cognitive operations do not fundamentally change with practice. Memory-based theories assume that automaticity is the result of a direct-memory retrieval process of past solutions from secondary or long-term memory. A technique is developed which permits an estimate of memory retrieval time in Experiment 3a. Application of additive factors logic suggests that memory retrieval and memory search and separate processes. Experiment 3b is proposed to compare the retrieval times of automatic and controlled processing. If the retrieval time decreases for CM conditions, but not VM conditions, this will provide support for memory-based theories. If the retrieval times do not differ between CM and VM conditions, this will provide support for process-based theories.

These experiments can be interpreted within the general framework proposed by Salthouse and Somberg (1982) which suggests that the acquisition of a skill is accompanied by three components: A) changes in the type of information processed, B) changes in the sequence of cognitive operations underlying performance, and C) changes in the attentional requirements. Experiments 1 and 2 cast doubt on component C and provide support for component A. Experiment 3 will provide evidence to evaluate component B.

A Componential Analysis of the Changes in Human Information

Processing with Consistent Practice

Practice can produce qualitative and quantitative changes in human performance. The improvement with practice follows a power function. Large performance gains occur early in practice while smaller improvements occur as the amount of practice increases (see Newell and Rosenbloom, 1981). Initial performance is typically characterized as slow, controlled, effortful, and capacity limited. After consistent practice, performance can be characterized as fast, automatic, fairly effortless, and free of capacity limits. In contrast, when the task structure varies from trial to trial, performance is less influenced by practice.

Several theories have been proposed (e.g., Shiffrin and Schneider, 1977; Schneider and Shiffrin, 1977; LaBerge and Samuels, 1974; Posner and Snyder, 1975; Logan, in press) to account for the performance differences resulting from the structure of the task. For example, Shiffrin and Schneider (1977) proposed a human information processing model which identified two modes of processing -- controlled and automatic. Controlled processing represents a temporary sequence of operations which are under the control of the subject, require active attention, and are capacity limited. Automatic processing represents a sequence of operations that always become active in response to a particular input. Automatic processes are insensitive to capacity limits and not directly under the control of the subject.

Controlled processing is used in novel situations, and is the result of a varied stimulus-response mapping (VM). Even after extensive practice, if the stimulus-response mapping is varied from trial to trial, subjects must rely on a controlled processing mode. In contrast, automatic processing

develops following consistent stimulus-response mapping (CM). If a stimulus is consistently mapped to a response, an efficient processing mode emerges with training which is insensitive to capacity limits. Early in training, performance is dominated by controlled processing. Following consistent practice, performance is dominated by automatic processing. In fact, consistency of practice is a critical factor in the development of automaticity (Schneider and Fisk, 1982b; Logan, 1979; but see Duncan, 1986; Durso, Cook, Breen, Schvaneveldt, 1987).

Several performance characteristics differentiate automatic and controlled processing. Three of the most commonly cited (e.g., Posner and Snyder, 1975; Shiffrin and Schneider, 1977; Schneider and Shiffrin, 1977; Logan, 1978; Schneider, Dumais, and Shiffrin, 1984; Schneider, 1985) characteristics are: a) the lack of an effect of memory load on performance in a Sternberg (1966) memory search task, (i.e., the zero or reduced slope criterion); b) the lack of an effect of the attention allocated to a non-automatic process on performance of an automatic process in dual task conditions, (i.e., perfect time sharing); c) a deleterious effect on performance of a non-automatic process when it is paired with an automatic process, (i.e., the intrusion effect). The co-occurrence of these properties has been used by several investigators to evaluate the internal consistency of the concept of automaticity (e.g., Logan, 1985; Papp and Ogden, 1981; Jonides, Naveh-Benjamin, and Palmer, 1985; Regan, 1981; Kahneman and Chajzyck, 1983).

Schneider (1985) proposed that the transition from controlled to automatic processing in a memory search task occurs in four phases. Phase one represents controlled processing and is characterized by an effect of memory load on performance in a memory search task. Phase two occurs

shortly after the introduction of consistent practice. In the second phase, controlled and automatic processing co-occur. Performance is the result of a mixture of responses generated by the two modes of processing. The more rapid of the two determines performance output. Phase two is characterized by a flattening of the memory load function for the larger set sizes. The flattening of the memory load function is attributed to an increase in the probability that automatic processing will finish prior to controlled processing as memory set-size increases. In phase three, the memory comparison process is eliminated as the controlled sequential operations are no longer necessary and processing shifts from serial to parallel. Phase three is characterized by the lack of an effect of memory load on performance. Subjects still allocate attention to the task in phase three; however, the attention serves to assist automatic processing. Phase four represents pure automatic processing and is characterized by the lack of an effect of memory load on performance and perfect time sharing between an automatic task and a secondary task which demands attentional resources. Thus allocating attention away from the automatic task or changing the difficulty of a concurrent task should produce no effect on performance in the automatic task. Furthermore, in dual task conditions, performance in the automatic task should be similar to single task performance levels.

This proposal addresses several issues concerning the development and properties of automatic processing. Experiment 1 evaluates the attentional demands of automatic processing as the processing priority is varied between a Sternberg task (either consistently or variably mapped) and a recognition running memory task which places demands on attentional resources. This is important because, at present, there is confusion in the literature concerning the attentional requirements of automatic processing. Automatic

processes have been described as not using processing resources and, at the same time, demanding attentional resources. One problem is that none of the studies examining the attentional requirements of automatic processing have used independent measures of the allocation of attentional resources. The attentional demands have been inferred solely by patterns of additivity and interaction between two tasks. In experiment 1, the attentional demands are evaluated by monitoring both overt behavioral and event-related brain potential (ERP) measures while manipulating the processing priority of the two tasks. Since the amplitude of the P300 component of the ERP varies as a function of the attentional resources allocated to a task, it can serve as an independent metric of the processing requirements of automatic and controlled processing.

Experiment 2 examines the changes in the microstructure of human information processing with consistent and varied practice. This is achieved through the joint use of additive factors logic and the P300 component of the event-related brain potential. Since the latency of the P300 component is sensitive to stimulus evaluation processing, but relatively insensitive to response selection and execution processing, this measure provides a useful metric for localizing the effects of practice and task structure. This approach permits the decomposition of overall performance into different processing components and the localization of improvement in performance with practice. This is important because the precise nature of the improvement in performance with practice can lead to a better understanding of the changes accompanying the acquisition of a skill. It is quite well known that practice improves performance. However, the mechanisms underlying the improvements are not well understood. In experiment 2, two tasks (a Sternberg memory search task and a pursuit

step-tracking task) were chosen which partially overlapped in the requirements for processing resources. It was predicted that since central processing resources do not overlap between the memory search task and the step-tracking task (step-tracking is primarily a perceptual-motor task, see Wickens, 1980), the imposition of the tracking task and the manipulation of its difficulty should not affect the development of automaticity of the memory search process. However, perceptual and motor processing resources should overlap between the two tasks, and it was therefore predicted that the imposition of the tracking task and the manipulation of tracking difficulty should interfere with the processing of these components of the task.

Experiment 3 contrasts two theories of automaticity -- process-based and memory-based. Process-based theories assume that the cognitive operations underlying a process become more efficient with practice; however, aside from becoming more efficient, the cognitive operations do not fundamentally change with practice. Memory-based theories assume that automaticity is the result of a direct-access memory retrieval of past solutions from secondary or long-term memory. A technique is developed which permits an estimate of memory retrieval time in Experiment 3a. Experiment 3b is proposed to compare the retrieval times of automatic and controlled processing. If the retrieval time decreases for CM conditions, but not VM conditions, this will provide support for memory-based theories. If the retrieval times do not differ between CM and VM conditions, this will provide support for process-based theories. These findings would provide important evidence for the mechanisms underlying the automatic processing components of a skill. A further goal of experiment 3 is to examine the time-course of changes in memory processing (both the memory comparison and

retrieval processes) with the development of automaticity. Memory-based theories predict that these processes should be coupled, while process-based theories predict that the two processes should be independent.

Experiment 1: The Attentional Requirements of Automatic Processing

An important issue concerning the distinction between automatic and controlled processing concerns the attentional requirements of the two modes of processing. The two process theory of Shiffrin and Schneider (1977, Schneider and Shiffrin, 1977) assumes that automatic processes do not require attention while controlled processes demand attentional resources. This seems to be at odds with the "automatic attention response" (Laberge, 1973; Shiffrin and Schneider, 1977; Shiffrin and Dumais, 1981; Schneider and Fisk, 1982b), where CM targets automatically attract attention from other ongoing activities. Shiffrin and Dumais (1981, p. 116-117) developed a two part rule to identify automatic processes, which focuses on the attentional requirements of the two modes of processing.

Rule 1: "Any process that does not use general, nonspecific processing resources and does not decrease the general, nonspecific processing capacity available for other processes is automatic."

Rule 2: "Any process that always uses general resources and decreases general processing capacity whenever a given set of external initiating stimuli are presented, regardless of a subject's attempt to ignore or bypass the distraction, is automatic."

A process that satisfies either rule 1 or rule 2 is considered automatic.

However, this definition lacks internal consistency. Rule 1 specifies that automatic processes do not require attentional resources, while rule 2 specifies that attentional resources are demanded by automatic tasks. If automatic processes do not require attentional resources, it is unclear why automatic processing automatically attracts attention. This results in an inefficient use of a valuable, limited capacity resource.

The allocation of attention is believed to be a dynamic, flexible process. Attentional resources are presumed to be sharable between tasks (Kahneman, 1973; Norman and Bobrow, 1975; Kantowitz and Knight, 1976; Navon and Gopher, 1979, 1980; Wickens, 1980). Initial formulations of resource models (e.g., Kahneman, 1973) proposed that there was a single, undifferentiated pool of resources available to all cognitive operations. The concept of an undifferentiated pool of processing resources has given way to the concept of multiple resources (Navon and Gopher, 1979, 1980; Wickens, 1980). Multiple resource theory holds that a number of processing units have their own supply of resources which can be shared by several ongoing cognitive operations. Wickens (1980) argued that processing resources could be defined by three dimensions: Stages of processing, codes of processing, and modalities of input and output. This framework has been used successfully to describe a number of dual task experiments. According to this logic, the greater the overlap in processing resources between two tasks, the more the two tasks interfere with each other. If two tasks place demands on separate pools of processing resources, then perfect time-sharing should occur.

Typical evidence used to bolster the assertion that automatic processes are resource insensitive comes from dual task studies (e.g., Bahrick, Nobel, and Fitts, 1954; Bahrick and Shelly, 1958; Schneider and Fisk, 1982b; Logan, 1978, 1979; Hirst, Spelke, Revese, Caharock, and Neisser, 1980) in which performance in a task which uses automatic processing is paired with a resource consumptive task. If performance in the two tasks remains at single task levels (i.e., perfect time-sharing), then it is assumed that automatic processing places few if any demands on the limited supply of attentional resources. For example, Logan (1978, 1979) employed additive factors

methodology (Sternberg, 1969b) to identify the attentional requirements of automatic and controlled processing. Both CM and VM memory search tasks were paired with a concurrent memory retention task. Initially, increases in RT as a function of memory load interacted with increases in the difficulty of the memory retention task, and this was taken as evidence that both CM and VM conditions placed demands on a limited supply of attentional resources. Following consistent practice, the effects of memory load and the difficulty of the memory retention task produced additive effects, while in VM dual task conditions an interaction between the two variables was observed. This pattern of results was taken as evidence that automatic processes do not place demands on attentional resources, since performance in the memory search task was unaffected by increases in difficulty of the concurrent memory retention task (which utilized attentional resources).

Additional evidence was reported by Schneider and Fisk (1982b). Subjects were able to simultaneously perform CM and VM tasks without any cost in detection sensitivity if subjects allocated attention to the VM task. If subjects allocated attention to the CM task, VM performance deteriorated dramatically. Furthermore, when two VM tasks were time-shared, performance on one task prospered at the expense of the other. These results were taken as support for the hypothesis that automatic processes do not require attentional resources; however, it was reported that subjects may still allocate attentional resources to the automatic task, unless explicitly instructed not to do so. This underscores the importance of dual task conditions in which the two tasks place similar demands on the multiple resource pools. If performance in the concurrent task is at single task levels and the tasks initially place demands on the same processing resources, then it reduces the probability that free attentional resources

will remain which can be allocated to automatic processing.

Shiffrin and Schneider (1977 exp. 4a-4d) provided evidence for the automatic allocation of attention to CM targets in a detection task (i.e., the automatic attention response). If a CM target was presented in an irrelevant position in the display, it interfered with the detection of VM stimuli in the attended locations. Thus the CM target, which was to be ignored, automatically drew attention away from the VM detection task. These results are seemingly at odds with the dual task literature described above. Thus, the attentional requirements of automatic processing remain unclear.

The research described above provided no independent measure of attentional investments underlying automatic and controlled processing. The attentional requirements were derived solely from patterns of dual task performance. Experiment 1 employs the traditional dependent measures of reaction time and A' , and in addition uses concurrent measures of ERPs to provide an independent measure of the attentional resources allocated to the task.

A number of dual task studies have reported a systematic relationship between the amplitude of the P300 component of the ERP and the perceptual/cognitive resources invested in a task (Isreal, Wickens, Chesney, and Donchin, 1980; Isreal, Chesney, Wickens, and Donchin, 1980; Natani and Gomer, 1981; Wickens, Kramer, Vanasse, and Donchin, 1983; Sirevaag, Kramer, Coles, and Donchin, submitted for publication; Kramer, Sirevaag, and Braune, 1987; Lindholm, Cheatham, Korinth, and Longridge, 1984). As primary task difficulty increased, the amplitude of the P300s elicited by the primary task increased. In contrast, the amplitude of the P300s elicited by the secondary task systematically decreased as primary task difficulty

increased. Thus, P300 amplitude exhibited a reciprocal relationship between primary and secondary tasks as a function of the difficulty of the primary task. Wickens et al., (1983) interpreted the reciprocity of P300 amplitude as evidence that the P300 is sensitive to the perceptual/cognitive resources allocated to a task. This follows from the assumption that primary and secondary tasks are competing for a finite amount of attentional resources and that as the difficulty of the primary task is increased, fewer resources are available for performance of the secondary task. Thus, variations in P300 amplitude can serve as a metric in the evaluation of the dynamic allocation of attentional resources used in performing a task.

Several studies have evaluated P300 amplitude in controlled and automatic processing conditions (Hoffman, Simon, and Houck, 1983; van Dellen, Brookhuis, Mulder, Okita, and Mulder, 1984; Hoffman, Houck, MacMillan, Simons, and Oatman, 1985; Kramer, Schneider, Fisk, and Donchin, 1986). As an illustrative example, Kramer et al., 1986 reported that CM and VM conditions produced equivalent results early in training. However, following practice systematic differences emerged for the CM conditions, but not the VM conditions which remained relatively unchanged with practice. For VM conditions, P300 amplitude varied inversely as a function of target probability and decreased with memory load. However, following consistent practice, P300 amplitude was insensitive to probability and memory load manipulations. Given that P300 amplitude is a sensitive measure of resource allocation, these effects suggest that processing resources were employed for both CM and VM conditions. However, all single task experiments are subject to the possibility that subjects allocated resources to the automatic task even though they were not required (cf. Schneider and Fisk, 1982b). Thus it remains an open question as to whether

attentional resources are necessary for the performance of an automatic task.

Hoffman, Houck, MacMillian, Simons, and Oatman (1985) examined the tradeoffs in P300 amplitude in a dual task paradigm as subjects shifted priorities between the tasks. The tasks were a CM memory search task and a dot detection task. P300 amplitude to the CM task was found to be large and relatively insensitive to changes in priority while there was a considerable decrease in P300 amplitude as priority was shifted away from the dot detection task. Unfortunately, it is difficult to determine which phase of automaticity (Schneider 1985) subjects were operating under in this experiment. Both reaction time and A' exhibited tradeoffs as a function of priority. Furthermore, since no VM condition was paired with the dot detection task, nor was performance early in training reported, it is unclear whether resource tradeoffs should be expected between these two tasks (cf. Wickens, 1980). Finally, the CM memory search task required simply a discrimination between digits and letters, hence the manipulation of memory load in this experiment is unclear (cf. Cheng, 1985).

Taken together, the results of the experiments examining the amplitude of the P300 component in automatic tasks have found large P300s elicited by these events. While it may be tempting to conclude from these studies that attentional resources were required in automatic tasks, one caveat should be noted. None of these experiments achieved phase four processing (e.g., Schneider, 1985) in which there are no effects of memory load on performance and there is perfect time-sharing between tasks. Furthermore, if resource tradeoffs are to be examined, it is important to manipulate processing priority between tasks which, at least prior to consistent practice, place demands on the same types of attentional resources (see Wickens, 1980).

Experiment 1 examines the attentional requirements of automatic processing. Given that performance meets the criteria of phase four processing (e.g., zero slope and perfect time sharing; Schneider, 1985), will automatic tasks elicit P300s and if so, will P300 amplitude trade off as a function of the processing resources allocated to the task? The present experiment contrasts controlled and automatic processes as they are time shared with a recognition running memory task, which places processing demands on the same types of attentional resources as the memory search task.

It was predicted that if automatic processes demand attention, then these events should elicit large P300s. If attention is automatically captured by automatic processing (i.e., the automatic attention response) then the amplitudes in dual task conditions should not trade off with priority and should not show a dual task decrement. In addition, the P300 amplitudes elicited in the dual task CM conditions should be relatively equivalent to the P300 amplitudes elicited in the single task VM conditions where attentional resources must be invested. In contrast, if automatic processes do not utilize or demand attentional resources, there should be little or no P300 activity elicited by these events. However, subjects may allocate spare capacity to the automatic processes even though unnecessary (Schneider and Fisk, 1982b). Thus if automatic processes do not require attentional resources but subjects choose to allocate then to the automatic process anyway, then P300 amplitude should vary as a function of processing priority. As the concurrent task priority increases, the spare capacity remaining to be allocated to the automatic task should diminish, resulting in a graded affect on P300 amplitude.

A second purpose of the present experiment was to examine differences

in automatic and controlled processing from a chronometric perspective. Several researchers have demonstrated that the peak latency of the P300 component is influenced by stimulus evaluation processes, but is relatively uninfluenced by response selection and execution processes (Kutas, McCarthy and Donchin, 1977; McCarthy and Donchin, 1981; Magliero, Bashore, Coles, and Donchin, 1984). Thus, P300 latency is affected by a subset of the processes which affect reaction time and therefore has proven useful in augmenting the chronometric information provided by reaction time (e.g., Duncan-Johnson, 1981).

Studies that have examined both reaction time and P300 latency in varied mapping memory search tasks report both measures increase as a function of memory load (e.g., Ford, Roth, Mohs, Hopkins, and Kopell, 1979; Strayer, Wickens, and Braune, 1987). In these studies, the effects of memory load were greater for reaction time than for P300 latency. This suggests that the reaction time slope which has been used as an index of memory search time, (e.g., Sternberg, 1966, 1969b, 1975), is multiply determined. A portion of the reaction time slope is related to stimulus evaluation processes, while another portion is related to response selection and execution processes which increase as a function of memory load (cf. Marcel, 1976).

A number of investigators have studied the effects of controlled and automatic processing on P300 latency (Hoffman et al., 1983; van Dellen et al., 1984; Kramer et al., 1986). Early in training both CM and VM conditions produced increases in reaction time and P300 latency as a function of memory load. Following consistent practice, both reaction time and P300 latency were unaffected by memory load. In contrast, the slope was relatively unchanged by practice in VM conditions. These results have been

taken to suggest that both the stimulus evaluation and response selection components of the memory comparison process become automated with consistent practice, but that even after extended practice, a serial memory comparison process is required for VM conditions.

Van Dellen et al., (1984) also reported that the RT intercept decreased for both CM and VM conditions, although the decrease was larger for CM conditions. The P3 latency intercept also decreased with practice for both conditions, but not to the same extent as RT. This suggests that both the stimulus evaluation and response selection and execution stages of processing improve with practice. Furthermore, reaction time preceded P300 latency following CM training, but not VM training, which is consistent with the hypothesis that the extraction of perceptual information became more efficient following the development of automaticity.

If the proposition that the extraction of perceptual information becomes more efficient following consistent practice is correct, then P300 latency should be uninfluenced by changes in priority under practiced CM conditions. Further, the relative timing of reaction time and P300 latency should not change as a function of priority. This follows from the hypothesis that the information extraction process is fine-tuned with consistent training and should therefore be less sensitive to changes in processing priority. In contrast, practiced VM conditions should produce tradeoffs in P300 latency as a function of priority. Further, the relative timing of reaction time and P300 latency should systematically vary as a function of priority under VM conditions. As attentional resources are withdrawn from the task, the stimulus evaluation processes should become further separated in time from the response selection and execution processes.

Methods: Experiment 1

Subjects

Five dextral subjects, 3 males and 2 females participated in the experiment. Their age ranged from 20 to 27, with an average age of 23. All were students from the University of Illinois with normal or corrected-to-normal vision. Subjects received extensive training, 23,000 trials, half in CM and half in VM conditions, prior to the experiment. Subjects were paid for their participation in the study.

Stimuli and Apparatus

The stimuli for the Sternberg task consisted of the letters B, D, F, G, H, J, N, P, T, V, X, Z. The stimuli for the running memory task consisted of the digits 1 to 9. The stimuli were displayed on a Hewlet Packard CRT that was positioned approximately 70 cm from the subjects. The stimuli were presented within a rectangle in the center of the display. The rectangle subtended a visual angle of 1.2 degrees vertically and 0.9 degrees horizontally. A Wico model 50-2010 joystick was used to record the subjects' responses.

Procedure

Subjects performed two tasks, both separately and together. The tasks were a Sternberg (1966) memory search task and a recognition running memory task. The Sternberg task consisted of the presentation of a memory set followed by 30 probe trials. Memory set sizes of 1 and 4 were employed and target and non-target trials were presented equiprobably. Targets were defined as items from the memory set, non-targets were items not included in the memory set. On each probe trial, two letters were presented simultaneously in the center of the display. On target trials, one of the two probes was a target while the other was a non-target. On non-target

trials, both probes were non-targets. Subjects were instructed to respond "target present" if any target was detected, and to respond "target absent" if neither probe was a target. A two position joystick was used for subjects to respond. The joystick was manipulated with the subjects' left hand. Subjects moved the joystick in one direction if a target was detected and moved the joystick in the opposite direction if they did not detect a target. The direction of movement was counterbalanced across subjects. Subjects were given 1500 msec to indicate their response. Instructions emphasized both speed and accuracy in single task conditions. Figure 1a

 Insert Figure 1 About Here

presents the temporal sequence of events. The memory set was presented for 3 seconds. 1500 msec following memory set offset, the probe stimuli were presented. Each probe stimulus was presented for 200 msec, with an interstimulus interval of 1650 msec.

An additional manipulation in the Sternberg task contrasted consistent mapping (CM) with varied mapping (VM). In the present experiment, the stimuli G, J, N, and X were consistently mapped targets. VM stimuli and CM non-targets were randomly drawn from the remaining letters (B, D, F, H, P, T, V, and Z).

The recognition running memory task consisted of a series of digits presented successively for 200 msec, with an interstimulus interval of 1650 msec. The subjects task was to move the joystick in one direction if the digit on trial N matched the digit presented on trial N-2. If the digit presented on trial N did not match the digit presented on trial N-2, the subject moved the joystick in the opposite direction. Subjects moved the

joystick in the same direction for targets in the Sternberg task as they did for match trials in the running memory task. The first two digits presented in the sequence had no item to compare with, hence subjects were instructed not to respond to the first two trials. Figure 1b presents an illustrative example. Consider the sequence 5, 3, 1, 3, 8, 4, ... 2. On trial 3, the subject should compare the digit 1 with the digit 5, which is stored in memory, and respond "mismatch". On trial 4, the subject should compare the digit 3 with the digit 3 held in memory, and respond "match". It is important to note that each stimulus served as a probe in the recognition task, and subsequently served as a template against which the digit presented two trials later was compared. For subjects to successfully perform the task, it was necessary for them to maintain the last two digits in memory. Digits were chosen randomly, with the constraint that match and mismatch trials were equiprobable. Subjects were given 1500 msec to indicate their response. Instructions emphasized both speed and accuracy in single task conditions. Prior to the experiment, subjects received 4260 trials of practice in the running memory task.

The two tasks (Sternberg and running memory) were performed in single and dual task conditions. In the dual task conditions, Sternberg and running memory trials were alternated successively. The interstimulus interval between trials remained at 1650 msec. The timing of events during each trial was identical to single task conditions. Figure 1c presents the temporal sequence of a block of trials. All blocks conformed to the following convention: RM, RM, M-Set, RM, S, RM, S, ... RM, S; where "RM" stands for a running memory trial, "M-Set" stands for the Sternberg memory set presentation, and "S" stands for a Sternberg probe trial. Five priority allocations were employed in the dual task configurations. They were as

follows: 1) 100% priority to running memory, 0% priority to Sternberg; 2) 90% priority to running memory, 10% priority to Sternberg; 3) Equal priority between tasks; 4) 10% priority to running memory, 90% priority to Sternberg; and 5) 0% priority to running memory and 100% priority to Sternberg. In the 100/0 and 0/100 priority conditions, subjects were instructed to perform only the 100% condition and ignore the 0% condition. Thus overt performance measures are not available for the 0% condition; however, ERP measures are available for these conditions. In the 90/10 and 10/90 conditions, subjects were instructed to perform the 90% task as well as they performed in the 100% condition, but they were to respond to the 10% condition using any remaining capacity. Thus the major difference between the 100/0 and the 90/10 conditions was that subjects were not responding to the 0% condition, but were responding to the 10% condition. Subjects practiced the dual task conditions for three days, (i.e., 60 blocks), prior to the experiment. It should be noted that the dual task conditions were extremely demanding. Initially, subjects reported that these conditions required all the effort that they could muster. Following consistent practice, subjects were able to perform the dual task conditions without deficit. Dual task VM conditions remained difficult throughout the experiment.

Experimental Design

The experiment included 2 set sizes (i.e., 1 and 4) X 2 response mapping conditions (i.e., CM and VM) in the Sternberg task. These conditions were performed in single task conditions. In addition, a single task running memory condition was performed. The two tasks were also combined to form dual task conditions. Five priority allocations, (i.e., 100/0, 90/10, 50/50, 10/90, 0/100, where the first number refers to the priority of the running memory task and the second refers to the priority of

the Sternberg task), were performed resulting in $2 \times 2 \times 5 = 20$ conditions. In all, 25 conditions were performed in each session, and subjects performed two sessions, with an average interval of 2, (range from 1 to 3), days between sessions. Performance in the two sessions was very stable, hence the two sessions were pooled for all analyses reported below. Each subject served in all experimental conditions. The order of experimental conditions was randomized across subjects and sessions.

ERP Recording

The electroencephalogram (EEG) was recorded from three midline sites (Fz, Cz, and Pz according to the International 10-20 system; Jasper, 1958) and referred to linked mastoids. Two ground electrodes were positioned on the left side of the forehead. Electrooculogram (EOG) electrodes were placed above and below the right eye. Electrode impedances did not exceed 10 KOhms. Beckman 10cm diameter Ag/AgCl biopotential electrodes were used at all electrode sites. Scalp electrodes were affixed with Grass EEG paste. Reference and ground electrodes were adhered with stomaseal adhesive collars.

The EEG and EOG were amplified with Van Gogh model 50000 amplifiers (time constant 10 sec and upper half amplitude of 35 Hz). Both EEG and EOG were sampled for 1300 msec, beginning 100 msec prior to stimulus onset. The data were digitized every 10 msec. The ERPs were digitally filtered offline (-3dB at 8.8 Hz; 0 dB at 20 Hz) prior to statistical analysis.

Stimulus Generation and Data Collection

Stimulus presentation and data acquisition were governed by a PDP 11/73 computer interfaced with an Imlac graphics processor (Donchin & Heffley, 1975; Heffley, Foote, Mui, and Donchin, 1986). Single trial EEG and EOG was monitored on line by using a GT-44 display. Digitized single trial data

were stored on magnetic tape for subsequent analyses. EOG artifacts were corrected off-line using a procedure described by Gratton, Coles, and Donchin (1983).

Results and Discussion: Experiment 1

Five dependent variables will be described: Reaction time, A' , P300 amplitude, P300 latency, and a ratio of Reaction time to P300 latency. Since it is important to establish that we have, in fact, met the criteria of automaticity (e.g., Schneider, 1985), we begin our discussion with measures of RT and A' .

Reaction time

Figure 2 presents the mean reaction time performance operator characteristic curves (POC). Performance in the Sternberg task is cross-plotted with performance in the running memory task for each level of priority. The upper right-hand region of the POC space represents good performance while the lower left-hand region represents poor performance. Changes along the diagonal connecting the lower left to the upper right-hand quadrant represents changes in the efficiency of performance. The greater the distance from the origin, the more efficient the performance. Changes along the diagonal connecting the upper left quadrant to the lower right quadrant represent changes in performance bias. Changes in priority allocation between tasks which compete for common resources should produce variations along the bias diagonal (Norman and Bobrow, 1975). POCs are drawn separately for CM and VM conditions and for target/match and non-target/mismatch trials. Set size 1 conditions are represented with squares and set size 4 conditions are represented with triangles. The least squares polynomial regression lines are fitted to the data. The solid lines are for the set size 1 conditions, the dashed lines are the regression

functions for the set size 4 conditions.

Perusal of figure 2 reveals that performance in the CM condition was

 Insert Figure 2 About Here

relatively constant and clustered in the upper right hand portion of the POC space, indicating rapid and efficient performance in both tasks.

Performance was little affected by memory load or by priority manipulations.

In contrast, performance in the VM condition was sensitive to both memory load and priority manipulations, (interactions: $F(1,4)=8.4$, $MSe=18,762$, $p<.05$ and $F(2,8)=6.1$, $MSe=13,394$, $p<.05$, respectively). These effects satisfy the reduced slope and perfect time-sharing criteria of automaticity.

Performance in the VM set size 1 condition was quite similar to that observed in the CM conditions. However, in the VM set size 4 condition, the POC was shifted to the lower left hand portion of the POC space, reflecting less efficient performance. Performance tradeoffs as a function of priority were evident in all conditions, although to a much greater extent in the VM conditions. Furthermore, performance traded off to a greater extent in the running memory task as a function of priority than in the Sternberg task (interaction: $F(2,8)=6.4$, $MSe=2,421$, $p<.05$). This suggests that subjects may have responded on the basis of a deadline in the Sternberg task. If this were in fact the case, we would expect that this "deadline strategy" would lead to an increased percentage of errors as subjects switched their priority from the Sternberg task to the running memory task. This prediction is addressed in the following section.

Performance Sensitivity

The parameter free estimate A' (Calderia, 1980; Craig, 1979; Green & Swets, 1966) was adopted to assess subjects sensitivity in all conditions. A' is a measure of the area under the received operator characteristic curve ranging from .5 for chance performance to 1.0 for perfect accuracy. A' is a more distribution free measure of sensitivity than d' and seems more appropriate when false alarm rates are very low as is the case in the CM conditions.

Figure 3 presents the mean A' POC curves. Performance in the Sternberg task is cross-plotted with performance in the running memory task for each

 Insert Figure 3 About Here

level of priority. POCs are drawn separately for CM and VM conditions. Set size 1 conditions are represented with squares and set size 4 conditions are represented with triangles. The least squares polynomial regression lines are fitted to the data. Like reaction time, performance in the CM condition was relatively constant and clustered in the upper right hand portion of the POC space. Performance was not affected by memory load or priority manipulations. This was also the case for the VM set size 1 condition; however, the VM set size 4 condition revealed a different picture. The POC for the VM set size 4 condition was shifted to the lower left portion of the POC space and revealed a reciprocal tradeoff in A' between tasks as a function of priority, (interaction: $F(2,8)=5.2$, $MSe=.0092$, $p<.05$). This is consistent with the hypothesis that subjects based their Sternberg response on a deadline, because reaction time did not vary as a function of priority in the VM set size 4 Sternberg condition while performance fell off rapidly

as emphasis was shifted from the Sternberg task to the running memory task. Thus it appears that subjects waited a constant duration in the Sternberg task and then based their response on the information which had accrued until that point.

Taken together, the results suggest that the automatic processing strategy developed in the CM conditions can be executed concurrently with the effortful processing in the running memory condition with little cost to either task. On the other hand, the controlled processing strategy employed in the VM conditions incurred a cost in terms of memory load effects in both single and dual tasks as well as performance tradeoffs in the difficult dual task conditions. Thus, performance satisfies the criteria for stage four processing (Schneider, 1985). Given that subjects are operating in a mode dominated by automatic processing, we now turn our attention to the ERPs elicited in the experiment. Since our first experimental question deals with the attentional resources required by automatic processes, we begin by examining the amplitude of the P300 component of the ERP.

Event-Related Brain Potential Data

Figure 4a presents a sampling of the average ERPs obtained in the experiment. Grand average Pz overplots are presented for CM and VM conditions as a function of priority for the running memory and Sternberg task memory load 4, target/match dual task conditions. Inspection of the waveforms reveals the classic N200-P300 pattern in all but the ignore conditions. The P300 is by far the most pronounced component in these averages. Figure 4b presents the latency adjusted waveforms for the same data.

 Insert Figure 4 About Here

P300 amplitude

Single trial P300 amplitude was estimated by identifying the largest correlation between a template (the positive segment of a .5 Hz sine wave) and the Pz electrode. The correlation was iterated at 10 msec lags from 300 to 850 msec. The maximum correlation between the template and the Pz electrode was used to identify the P300 component. Trials in which the maximal correlation was less than $r=.30$ were rejected. Only trials in which subjects' responses were correct were examined, with the exception of trials in which subjects were instructed not to respond (i.e., the 0% priority conditions for each task).

Figure 5 presents the P300 amplitude POC curves. Performance in the Sternberg task is cross-plotted with performance in the running memory task

 Insert Figure 5 About Here

for each level of priority. POCs are drawn separately for CM and VM conditions and for target/match and non-target/mismatch trials. Set size 1 conditions are represented with squares and set size 4 conditions are represented with triangles. The least squares polynomial regression lines are fitted to the data. Boxlike POCs are apparent for the CM conditions, and for the VM set size 1 conditions. Performance in these tasks was generally in the upper right-hand portion of the POC space, indicating efficient performance with little tradeoff between the two tasks. The tails

of the POC were drawn away from the upper right-hand quadrant by the 0% conditions in each task, which resulted in substantially reduced P300 amplitudes. In contrast, the POCs for the VM set size 4 conditions reveal a reciprocal relationship between the two tasks as a function of priority. While P300 amplitude to the Sternberg trials increased as priority was shifted from the running memory task to the Sternberg task, there was a concomitant reciprocal decrease in P300 amplitude to the running memory trials, (interaction: $F(2,8)=5.3$, $MSe=2,548$, $p<.05$). Yet the sum of the P300 amplitudes for the two tasks at a given priority was a constant, $F(2,8)=0.1$, $MSe=183$, $p>.9$. Thus P300 amplitude seems to reflect a fixed capacity in response to changes in resource allocation. It is interesting to note that while the sum of the amplitudes within a condition yielded a constant total amplitude, this constant was greater for the CM conditions than for the VM conditions, (interaction: $F(2,8)=11.6$, $MSe=1,909$, $p<.01$). Thus in the Sternberg task, P300 amplitudes elicited in the CM conditions were larger than the P300 amplitudes elicited in the VM conditions; however, this effect diminished as subjects allocated more attention to the VM Sternberg task, (interaction: $F(4,16)=4.1$, $MSe=4,642$, $p<.01$). This implies that automatic processes tend to evoke larger P300s than controlled processes, unless subjects allocate attentional resources to the task.

An additional comparison examining the P300 amplitudes elicited in the 100/0 priority condition revealed that in the Sternberg task CM targets elicited larger P300s than the VM probes or CM non-targets. This effect was coupled with the finding that the P300s elicited by the running memory task in the 100/0 priority condition were smaller for CM conditions than for VM conditions. This effect suggests that when CM targets are presented they automatically attract attention away from the concurrent task. Thus the

presence of the CM target intrudes on the performance of the running memory task, even when subjects were instructed to ignore the Sternberg stimuli.

Taken together, the data suggest that the running memory task and the VM set size 4 Sternberg condition utilized common resources, since P300 amplitude varied reciprocally as a function of the resources allocated to the task. This was not the case for the easy VM condition (i.e., set size 1), nor was it the case in the CM conditions. This suggests that automatic tasks may develop the ability to tap different pools of attentional resources (cf. Logan, in press) or perhaps the demands did not exceed the supply (i.e., common resources were still utilized but the demands on these resources were low for the easy CM and VM conditions and for the difficult CM condition).

In sum, large P300s were elicited by the CM Sternberg probes and P300 amplitude remained relatively constant across different priority conditions. In contrast, the P300s elicited by the VM Sternberg probes varied as a function of priority allocation and memory load. Given that P300 amplitude is sensitive to the perceptual/cognitive resources allocated to a task, this pattern of results suggests that attentional resources are allocated to automatic processes. It should be noted that the allocation of attentional resources is not obligatory. In the ignore condition (100/0) P300 amplitudes were substantially reduced. It appears that subjects must be engaged in the task for attentional resources to be invested. Thus the automatic processing of stimuli can be suppressed; however, the intrusion of the CM task on running memory performance in the 100/0 priority condition suggests that some processing of the automatic targets occurred and that this processing diminishes the pool of attentional resources which can be invested in processing of concurrent tasks. Thus automatic processing can

be suppressed, but perhaps not totally eliminated.

There are at least two different ways to achieve the reciprocity of P300 amplitude in the VM set size 4 conditions. First, all stimuli could elicit smaller P300s as attention was withdrawn from the task. Second, some stimuli could elicit "normal" P300s while other stimuli could elicit no P300s. A pattern of reciprocity could be obtained if the mixture of normal P300s and no P300s varied as attention was withdrawn from the task. These two alternatives imply different mechanisms underlying dual task performance. The former suggests that the tasks were processed in parallel and that attentional resources were partitioned according to instructions at any moment in time. The latter implies that subjects time-swapped attention between tasks and that attention operated as a unit which was not partitioned according to instruction. Instead, subjects may have spent proportionally more time processing the higher priority task, increasing the probability of having attention allocated to the task when a stimulus was presented. These two types of processing suggest different distributions of P300 amplitude. If subjects are dividing attention between tasks, then one would predict a unimodal distribution which shifts according to priority. In contrast, if subjects are time-swapping between tasks, the distribution of P300 amplitude should reflect a mixture of large and small P300s. As priority is withdrawn from a task, there should be an increase in the proportion of no P300s and a decrease in the proportion of normal P300 trials. Examination of the distributions of P300 amplitude in the present experiment revealed a unimodal distribution which varied as a function of priority. Thus the present data suggest that attentional resources were partitioned according to instruction and that the two tasks were processed in parallel.

One final comment concerning the tradeoffs in P300 amplitude as a function of priority merits discussion. P300 amplitude changed most rapidly at the extreme priority conditions and was less affected by priority over the intermediate priority conditions. This could imply that attentional resources are allocated in chunks. The intermediate priority conditions may represent conditions utilizing relatively similar chunks of attention. In otherwords, there may be a limit on the divisibility of attentional resources between tasks. It remains for future research to determine if the priority resource function would become more linear with extended practice.

Mental Chronometric Analysis

We now turn our attention to the second issue addressed by Experiment 1. It was predicted that if the extraction of perceptual information is more efficient following the development of automaticity as the result of a fine tuning of a perceptual filter, then P300 latency should be uninfluenced by changes in priority under practiced CM conditions and the relative timing of reaction time and P300 latency should not change as a function of priority. In contrast, practiced VM conditions should produce tradeoffs in P300 latency as a function of priority and the relative timing of reaction time and P300 latency should vary as a function of priority.

P300 latency

Single trial P300 latency was estimated by identifying the largest positivity in the Pz electrode between 300 and 850 msec. Only trials in which subjects' responses were correct were examined, with the exception of trials in which subjects were instructed not to respond (i.e., the 0% priority conditions for each task).

Figure 6 presents the P300 latency POC curves. Performance in the Sternberg task is cross-plotted with performance in the running memory task

for each level of priority. POCs are drawn separately for CM and VM

 Insert Figure 6 About Here

conditions and for target/match and non-target/mismatch trials. Set size 1 conditions are represented with squares and set size 4 conditions are represented with triangles. The least squares polynomial regression lines are fitted to the data. Inspection of the POCs reveals several interesting effects. For the target/match CM condition, the POCs are boxlike and overlapping for the two different memory loads. Performance generally falls in the upper right-hand portion of the POC space except for the 100/0 and 0/100 priority conditions, which represent the single task variants of the two tasks. This trend was also apparent for the target/match VM set size 1 condition. However, for the target/match VM set size 4 condition, P300 latency varied as a function of priority for the running memory task, but not for the Sternberg task. This trend is similar to that reported for reaction time and provides further support that subjects based their response in the Sternberg task upon a deadline criterion. For non-target/mismatch conditions, P300 latency was less affected by changes in priority, and this was more pronounced in the Sternberg task, (interaction: $F(4,16)=6.2$, $MSe=10,296$, $p<.01$). Overall, P300 latency exhibited a reciprocal relationship between the running memory task and the Sternberg task in the VM conditions. As priority was shifted from the running memory task to the Sternberg task, P300 latency increased in the running memory task and decreased in the Sternberg task, (interaction: $F(4,16)=6.8$, $MSe=47,458$, $p<.01$).

Taken together, these results are consistent with the predictions that

P300 latency should be relatively uninfluenced by changes in priority in the CM condition, but should vary with priority in the VM condition. The results imply that the duration of the stimulus evaluation processes are relatively constant following consistent practice. We now turn to the second prediction concerning the relative timing of reaction time and P300 latency. It was predicted that the relative timing of reaction time and P300 latency should not vary with priority under CM conditions, but should under VM conditions.

RT/P300 latency Ratio

A ratio of reaction time to P300 peak latency was derived for each single trial to determine the proportion of post-stimulus evaluation processing in each condition. A ratio of 1.0 indicates that the overt response and the P300 peak occurred simultaneously. Ratios less than 1.0 indicate that the response preceded the peak latency and ratios greater than 1.0 indicate that the response was emitted after the P300 peak.

Figure 7 presents the RT/P300 ratio POC. Performance in the Sternberg task is cross-plotted with performance in the running memory task for each

 Insert Figure 7 About Here

level of priority. POCs are drawn separately for CM and VM conditions and for target/match and non-target/mismatch trials. Set size 1 conditions are represented with squares and set size 4 conditions are represented with triangles. The least squares polynomial regression lines are fitted to the data. Performance in the CM conditions and in the easy VM conditions lie in the upper right-hand region of the POC space, indicating efficient performance. In contrast, VM set size 4 conditions resulted in less

efficient performance which varied as a function of priority.

These results are consistent with the hypothesis that extraction of perceptual information is more efficient following consistent training. The RT/P300 ratio remained relatively uninfluenced by changes in priority under CM conditions, but varied as a function of priority in VM conditions. Further, the RT/P300 ratio was below 1.0 for all CM conditions; however, in the set size 4 VM conditions, the RT/P300 ratio was greater than 1.0 for all dual task conditions. Taken together, these results suggest that an efficient information extraction process emerges following consistent practice (i.e., RT precedes P300 latency). Laberge (1981) described this as a within system (i.e., perceptual system) automatization where the unitization of perceptual patterns converges a set of feature detectors into a higher-order representation or code. It is as if a perceptual filter is fine-tuned with consistent practice to efficiently process automatic targets, while the extraction of non-automatic targets is resource consumptive.

Given the differential pattern of RT/P300 ratios for CM and VM conditions, it suggests that more post-stimulus evaluation is engaged in under VM conditions. Thus a good deal of this processing is related to response selection and execution processes, since P300 latency is unaffected by these processes. It is worthwhile noting that Experiment 2 (to be described below) found that VM performance improved with practice, but that the nature of this improvement was post P300. Since subjects responded "yes" consistently with one button, and "no" consistently with another it suggests that the response selection and execution processes may become automated to some extent with consistent practice. Similar conclusions were drawn by Shiffrin and Dumias (1981) with respect to the decrease in the

intercept under VM conditions. These results imply that different processing stages can operate in conjunction under different modes of processing.

Conclusions: Experiment 1

Experiment 1 addressed the question of whether automatic processes require attentional resources. It was predicted that if automatic tasks require attentional resources, then large P300s should be elicited by these events. If automatic processing automatically captures attentional resources, then P300 amplitude should not vary as a function of processing priority. In contrast, if automatic processes do not require attentional resources, then large P300s should not be elicited by these events, or if P300s are elicited they should vary as a function of processing priority. The results support the interpretation that automatic processing requires attentional resources. Large P300s were elicited in the CM conditions and P300 amplitude did not vary with changes in processing priority. These findings are consistent with the notion of an automatic attention response (Shiffrin and Schneider, 1977). The presentation of a CM target automatically draws attention to the processing of the stimulus.

A second issue addressed in the present research dealt with the proposition that the extraction of perceptual information is more efficient following the development of automaticity. It was predicted that if this proposition was correct then P300 latency should be relatively uninfluenced by changes in processing priority under practiced CM conditions and that the relative timing of RT and P300 latency should not change as a function of processing priority. In contrast, it was predicted that practiced VM conditions should produce tradeoffs in P300 latency as a function of priority. Furthermore, the relative timing of RT and P300 latency should

vary systematically as a function of priority. The results supported these predictions and suggests that the extraction of perceptual information becomes more efficient following consistent practice. It is important to note that prior to CM training, performance in CM and VM conditions was comparable. Thus, any changes in the relative timing of feature extraction must be the result of consistent practice. These results imply that one aspect of the development of automaticity includes a refinement in the extraction of perceptual information. This is consistent with the subjective report that CM targets "pop out" of the display (e.g., Neisser, 1967; Shiffrin and Schneider, 1977). Thus the perceptual system is tuned via consistent practice.

Experiment 2: An Analysis of the Time-Course of Automaticity

Experiment 1 suggested that the extraction of perceptual information is more efficient following consistent practice and that attentional resources are used in automatic processing. These findings can be interpreted within a general framework proposed by Salthouse and Somberg (1982) which suggest that the underlying components of a task may be differentially affected by task structure and practice. According to Salthouse and Somberg, the improvements accompanying the acquisition of a skill are due to A) changes in the type of information being processed, B) changes in the sequence of cognitive operations underlying the task, and C) changes in the attentional requirements of the task. Component A may reflect a refinement of the perceptual system to attend only to relevant dimensions of the task, which may result in changes in component C. Likewise, changes in component B may reflect a transition from serial to parallel processing, which also may result in changes in component C. These changes may account for the qualitative and quantitative changes in performance which accompany the

acquisition of a skill.

Experiment 1 casts doubt on reductions in the attentional requirements of automatic processing (component C) as indexed by P300 amplitude. However, evidence from the mental chronometric analysis provided some evidence for a refinement in the perceptual system to attend only to relevant dimensions of the task (component A). The purpose of experiment 2 is to further explore the developmental changes in information processing that takes place over a sustained period of training (e.g., > 20,000 trials). Experiment 2 focuses on the changes in human information processing with consistent and varied practice in a Sternberg memory search task. A fine-grained analysis of the changes in performance and information processing strategies as a function of practice and task structure will be accomplished through the joint use of additive factors logic and the P300 component of the ERP. Since P300 latency is influenced by the duration of stimulus evaluation processes, but is relatively unaffected by changes in response selection and execution, the combined use of RT and P300 latency can be used to decompose the information processing demands of the component processes underlying the Sternberg memory search task. Two tasks, a Sternberg memory search task and a pursuit step-tracking task, were employed in the experiment. The step-tracking task was selected because it places demands on perceptual and motor processing resources, but does not interfere with central (memory search) processes (see Wickens, 1980). Thus, these two tasks competed for perceptual and motor resources, but not for the resources utilized by the memory comparison process. This combination of tasks with partially overlapping resource demands allows us to examine the influence of perceptual-motor demands on the development of the automatic processing of the memory comparison process. The question, therefore, is whether these demands will impede the

development of perceptual-motor automaticity.

It was predicted that the memory comparison process would be uninfluenced by the imposition of a tracking task and the increases in its difficulty. Furthermore, the development of automatic processing (reflected by the zero slope) should not be affected by the tracking task, since the tracking task and the memory comparison process demand separate resources. In contrast, the perceptual and motor components of the task were predicted to be influenced by the tracking task and its difficulty early in training. However, following practice, the non-memory search components of the Sternberg task (i.e., perceptual encoding and response selection and execution) which were consistent throughout the experiment were predicted to be uninfluenced by the tracking task.

In the present experiment, seven subjects received ten sessions of CM and VM practice. Subjects practiced the step-tracking task and the Sternberg task both separately and in dual task conditions. In dual task conditions, subjects were instructed to maintain single task performance in the step-tracking task at the expense of performance in the Sternberg task. Two levels of tracking difficulty (first and second order) were used. It was predicted that dual task interference would be obtained early in training for the non-memory search components of the Sternberg task. However, following consistent practice these components would be uninfluenced by the dual task. In contrast, this should not be the case for the components of the Sternberg task which are not consistent throughout the experiment.

Methods: Experiment 2

Subjects

Seven right-handed persons (4 male and 3 female), aged 22 to 27 years, were recruited from the student population at the University of Illinois and paid for their participation in the study. None of the students had any prior experience with either of the experimental tasks. All of the subjects had normal or corrected to normal vision. Each of the subjects participated in the ten experimental sessions.

Insert Figure 8 About Here

Step Tracking and Sternberg Tasks

The single axis pursuit step tracking task is illustrated, along with the Sternberg probes, in Figure 8. The tracking display which consisted of the computer driven target and the subject controlled cursor was presented on a Hewlett Packard CRT which was positioned approximately 70 cm from the subjects. The rectangular target was 1.5 cm x 1.1 cm in size and subtended a visual angle of 1.2 degrees horizontally and .9 degrees vertically. The cursor consisted of one vertical and two horizontal .8 cm lines, and subtended a visual angle of 2.4 degrees horizontally and .9 degrees vertically. The target changed its position along the horizontal axis once every 1.5 sec and the subjects' task was to nullify the position error between the target and cursor. The target could jump anywhere along the horizontal axis. The magnitude and direction of the jump were randomly determined on each trial. The cursor was controlled by manipulating a joystick with the right hand. Single task tracking blocks were comprised of 100 step changes and lasted approximately two and a half minutes. Although

changes in the spatial position of the target were discrete events, the tracking task was performed continuously since the subjects were required to constantly manipulate the joystick to nullify the position error between the target and cursor.

The dynamics for the tracking stick were composed of a linear combination of first order (velocity) and second order (acceleration) components. That is, the system output, $X(t)$, is represented by the following equation.

$$X(t) = [(1-a) \int u(t) dt] + [a \int \int u(t) dt^2]$$

where: u = stick position; t = time and a = difficulty level.

The task was conducted at two different levels of the system order manipulation: (1) in the first order (velocity) condition a was set to zero while (2) in the second order (acceleration) condition a was set to 1.0. Numerous investigators have validated the increasing difficulty associated with higher order control (Kramer et al., 1983; North, 1977; Trumbo, Noble and Swink, 1967; Vidulich and Wickens, 1981). Converging evidence employing Sternberg's additive factors paradigm indicates that the demands of higher order tracking are both perceptual and motor in nature, given the requirement to process higher derivatives of the error signal to maintain stable control (Wickens, Derrick, Micallizi and Beringer, 1980).

In the Sternberg task, subjects were instructed to decide if one of two letters presented on a CRT belonged to a previously memorized set of letters. A match will henceforth be referred to as a target trial while a mismatch will be labeled as a non-target trial. Each set of thirty trials began with a six sec presentation of a memory set of either two, three or four letters. In the 30 trials that followed the presentation of each memory set, the subjects' task was to deflect a joystick in one direction if

one of the two probe items matched an item from the memory set and in the opposite direction if neither of the letters were from the memory set. The joystick was manipulated with the left hand. The direction of the deflection of the joystick for the two responses was counterbalanced across subjects. The two probe items were presented simultaneously for a duration of 200 msec. The ISI was 1500 msec. Subjects were given 1200 msec to indicate their response. Responses prior to 150 msec and after 1200 msec following stimulus onset were scored as incorrect. Instructions emphasized both speed and accuracy.

Two variables served as blocking factors within the Sternberg task. First, subjects performed the task in both CM and VM conditions. In the CM condition, targets were always selected from one set of letters (G,J,N,X) while distractors were selected from another set of letters (P,H,Z,B,F,D,V,T). In the VM condition both targets and distractors were chosen from the same set of letters (P,H,Z,B,F,D,V,T). Targets and distractors exchanged roles over trials in the VM condition. The second blocking factor was the number of items in the memory set. Subjects performed the task with either two, three or four memory set items. A third factor, the probability of a target or non-target trial was fixed at .50 in each block. On a target trial, one of the items was a target and the other was a distractor. The targets occurred equally often on the left and right. On a non-target trial, both of the items were distractors. The Sternberg probes were presented within the target in the tracking task.

In the dual-task blocks subjects concurrently performed the tracking task and the Sternberg task. Pursuit step tracking was defined as the primary task. Thus, in these conditions subjects were required to encode a set of memory items, respond to the presentation of the probes and minimize

tracking error. Subjects used the left joystick for their discrete responses in the Sternberg task and the right joystick for their continuous responses in the tracking task. Following each block of trials the subjects were informed of their RT and accuracy in the Sternberg task and the average root mean square (RMS) tracking error.

 Insert Figure 9 About Here

The temporal sequence of the trials in the dual-task conditions is graphically illustrated in Figure 9. The sequence proceeded as follows: The subjects began tracking changes in the spatial position of the target. Two spatial changes in the target occurred with an ISI of 1.5 sec. At this time, the Sternberg memory set was presented for 6 sec in the center of the CRT, above the tracking task. Following presentation of the memory set, the changes in the spatial position of the tracking target alternated with the occurrence of the Sternberg probes. After the occurrence 60 events, another memory set was presented, followed by another 30 Sternberg probes and 30 changes in the position of the target in the tracking task. Thus, each dual-task block was composed of two different Sternberg memory sets, 60 presentations of Sternberg probes and 62 changes in the position of the target in the tracking task. Dual-task blocks lasted approximately 200 seconds.

ERP Recording System

Electroencephalographic activity (EEG) was recorded from three midline sites (Fz, Cz and Pz according to the International 10-20 system: Jasper, 1958) and referred to linked mastoids. Two ground electrodes were positioned on the left side of the forehead. Beckman Biopotential electrodes affixed

with Grass paste were used for scalp, mastoid and ground recording. Beckman electrodes, affixed with adhesive collars, were also placed below and supra-orbitally to the right eye to record electro-oculogram (EOG). Electrode impedances did not exceed 10 kohms.

The EEG and EOG were amplified with Van Gogh model 50000 amplifiers (time constant 10 sec and upper half amplitude of 35 Hz, 3dB octave roll-off). Both EEG and EOG were sampled for 1300 msec, beginning 100 msec prior to stimulus onset. The data was digitized every 10 msec. ERP's were filtered off-line (-3dB at 6.29 Hz, 0dB at 14.29Hz) prior to statistical analysis. Evaluation of each EOG record for eye movements and blinks was conducted off-line. EOG contamination of EEG traces was compensated for through the use of an eye movement correction procedure (Gratton, Coles & Donchin, 1982).

Design

A repeated measures, five way factorial design, was employed. The factors were single/dual task conditions (single task Sternberg, Sternberg with first order tracking, and Sternberg with second order tracking), the structure of the Sternberg task (CM or VM), memory set size (2, 3, or 4), session (1 and 10), and the type of Sternberg trial (target or non-target). The first four variables served as blocking factors, the fifth factor was varied within blocks. Subjects also performed single task tracking blocks with first and second order control dynamics.

Procedure

Each of the seven subjects participated in all of the experimental conditions. Ten experimental sessions, within a three week period, were required to complete the experiment. In sessions one and six through ten, subjects performed two replications of the dual and four replications of the

single task conditions. Thus, in these sessions subjects completed 24 dual-task blocks comprised of 120 trials each and 32 single task blocks each composed of 60 trials. Dual-task blocks took approximately 3.5 minutes each while single task conditions required 1.5 minutes each. Subjects were permitted to take brief rest breaks between each of the blocks and longer breaks whenever necessary. Each of these sessions lasted approximately 2.5 hours.

In sessions two through five, subjects performed five replications of the six single task Sternberg conditions (task structure x set size). Thus, during these sessions subjects completed 30 blocks of trials, each requiring approximately 1.5 minutes. These sessions lasted 1 hour each. The order of presentation of experimental blocks was counterbalanced across subjects in each of the sessions. Subjects performed 20,160 Sternberg probe trials over the ten sessions, 10,080 each in the CM and VM conditions. The tracking task, in both single and dual-task conditions, was performed for approximately nine hours.

RT and accuracy measures were recorded in the Sternberg task throughout the ten sessions. RMS tracking error was recorded in session one and six through ten. ERPs were recorded during the presentation of the Sternberg probes in the first and last sessions.

Data Analysis

RT in the Sternberg task was defined as the interval between the appearance of the probes and the subject's response. RMS error in the tracking task was calculated every 50 msec during single and dual-task conditions. This data was averaged off-line according to experimental condition.

The single-trial ERPs acquired during single and dual-task Sternberg

performance were averaged separately for each of the experimental conditions in sessions 1 and 10. Each of the single-subject averages was composed of at least 50 single trial ERPs. The amplitude and latency of the P300 component was quantified in the following manner. On each single-trial P300 amplitude was measured as the difference between the maximum positive deflection between 300 and 900 msec after the presentation of the probes and the baseline, that was defined as the average voltage recorded over the 100 msec epoch just preceeding the stimulus array (Coles, Gratton, Kramer and Miller, 1986). The latency was defined as the time at which the P300 reached its maximum amplitude.

Results and Discussion: Experiment 2

This section is organized in the following manner. First, the results for the single tasks will be presented for the first and last experimental sessions. This is done to demonstrate that we have replicated the effects of task structure and practice on measures of performance and to illustrate how psychophysiological measures might be used to explicate changes in cognitive processes. Next will follow a comparison of the results obtained in the single and dual task conditions, contrasting the transition from single to dual tasks as well as examining the effects of an increase in the difficulty of the tracking task on Sternberg performance. Several dependent measures are examined in both the single and dual-task analyses. These include: reaction time (RT), accuracy, RMS error in the tracking task, measures of the amplitude and latency of the and P300 component of the ERP, and the RT/P300 ratio in the Sternberg task.

Performance measures

Figure 10a presents the average RTs for the CM and VM conditions and the three memory set sizes in sessions 1 and 10. As suggested by the

Insert Figure 10 About Here

figure, subjects performed the Sternberg task more quickly in session 10 than they did in session 1 ($F(1,6)=19.0$, $p<.01$, $MSe=490,320$). RT was faster in the CM than in the VM conditions ($F(1,6)=47.2$, $p<.01$, $MSe=325,070$). The analysis also indicated that the effect of memory set size decreased with practice for CM conditions, but not for VM conditions ($F(2,12)=10.9$, $p<.01$, $MSe=23,540$). The differences in memory set effects between CM and VM conditions as a function of practice are further supported by the memory set slopes obtained in a series of regression analyses performed on these conditions. The slope and intercept parameters for these conditions are presented in table 1.

Insert Table 1 about here

Thus, in session 1 RTs increased as a function of set size for both CM and VM conditions. In session 10, after subjects had received over 20,160 trials of practice, memory set size still produced a significant effect in the VM conditions. However, in the CM conditions, the size of the memory set did not have a significant effect on RT.

The pattern of RTs produced in the CM and VM conditions is consistent with previous findings and fulfills the "zero slope" criterion for automaticity. (Shiffrin and Schneider, 1977; Shiffrin, Dumais and

Schneider, 1981). Even extensive practice does not improve memory search performance when subjects are unable to consistently map stimuli to responses. However, when subjects are able to consistently map stimuli to responses, performance improves such that the time required to compare two probes to four items in memory does not significantly differ from the time required to compare the probes to two memory set items.

It is important to note that performance does improve in the VM conditions with practice. However, this decrease in RT was in the intercept, not the slope. In the CM conditions both the intercept and memory set size slope decreased with practice. This observation of decreased RT in the VM conditions is not new. In fact, it has been hypothesized that the improvement in performance may be attributed to familiarization with the task instructions, equipment useage, or selection of strategies (Ackerman, in press) or the automatization of consistent components of the task (Schneider, Dumais and Shiffrin, 1984). Unfortunately, at the present time these hypotheses remain untested. One strategy for examining these differences in performance is to analyze the changes in RT within the framework of Sternberg's (1966, 1969b) additive factors methodology. Within such a framework the pattern of results obtained in the present study would suggest that either encoding and/or response processes become more efficient in both the VM and CM conditions, while the need for memory comparison processes diminishes in the CM but not in the VM conditions. The distinction between encoding and response demands will be addressed by the analysis of P300 latency.

Figure 10b and c presents the mean RT values for first and second order tracking conditions. The linear regression slope and intercept parameters are also presented in table 1. It is apparent that the trends reported in

single task conditions were obtained in dual task conditions, for both first and second order tracking. In addition, there was a systematic increase in the intercept from the single task Sternberg conditions to the dual task first order tracking condition, and a further increase in the intercept in the second order tracking condition ($F(2,12)=3.7$, $p<.05$, $MSe=69,706$). Within the context of Sternberg's additive factors logic, this suggests that the imposition of the tracking task and the manipulation of its difficulty produced increases in either encoding and/or response selection time. The distinction between the encoding and response demands will be addressed in more detail in the analysis of P300 latency.

The effects of memory load on single task reaction time produced equivalent effects under dual task first order tracking conditions. However, there was a decrease in the memory set size slope in the second order dual task conditions ($F(4,24)=3.8$, $p<.01$, $MSe=5931$). Given that this effect occurred early in training for both CM and VM conditions, it is unlikely that this effect is due to practice. Traditional explanations for similar patterns of underadditivity (e.g., McClelland, 1979, Pashler, 1984) would suggest that some parallel processing of the step-tracking and Sternberg task occurred in the second order dual task conditions.

A further decomposition of the changes in processing with practice can also be provided by an examination of the response type variable. Although we did not explicitly manipulate the number of display comparisons, as has been done in other investigations of automatic and controlled processes, we did present the target items on both the right and left side of the frame. On half of the target trials a memory set item appeared on the left and a distractor on the right while this arrangement was reversed on the other half of the target trials. Since the probes were presented within a 1.2

degree visual angle for 200 msec, it was unlikely that subjects moved their eyes to scan the display for a target. However, as is apparent in figure 11, subjects did appear to shift their attention from the left to the right

 Insert Figure 11 About Here

when performing in the VM conditions. It took subjects 34 msec longer to respond to the target when it appeared on the right than it did when the target occurred on the left of the frame ($F(1,6)=6.2$, $p<.05$). In the CM conditions, RT was not influenced by the position of the probe ($p>.48$). Non-target trials took longer to respond to than target trials in both CM and VM conditions. It is interesting to note that this relationship between response type and task structure did not interact with the amount of practice ($F(2,12)=0.69$, $p>.10$, $MSe=348$). This would imply that the rapid and apparently parallel display processing strategy exhibited in the CM condition developed within the first 1440 trials of practice, far more quickly than the decrease in the memory set slope.

Figure 12a presents the average error rate for the CM and VM conditions and the three memory set sizes in sessions 1 and 10. The pattern of results

 Insert Figure 12 About Here

was quite similar to that obtained for RT. Subjects made significantly more errors when performing in the VM conditions than they did in the CM conditions ($F(1,6)=29.9$, $p<.01$, $MSe=87.15$). Further, error rate decreased from session 1 to session 10 and this effect was greater for VM conditions ($F(1,6)=10.5$, $p<.01$, $MSe=2.62$). Error rate also increased as a function of

memory set size ($F(2,12)=8.5$, $p<.01$, $MSe=24.44$) and response type ($F(1,6)=13.6$, $p<.01$, $MSe=47.15$). This latter effect was greater for VM conditions ($F(1,6)=53.7$, $p<.01$, $MSe=25.15$). Since higher error rates were associated with longer RTs, these data suggest that subjects were not trading speed for accuracy while performing the Sternberg task.

Figure 12b and c present the error rate means for first and second order conditions. The trends obtained in single task conditions were also obtained in dual task conditions. In addition, error rate increased from single task conditions to dual task first order conditions, and increased further in dual task second order conditions ($F(2,12)=9.5$, $p<.01$, $MSe=38.4$). This trend was more pronounced in session 1 than in 10 ($F(2,12)=11.5$, $p<.01$, $MSe=23.4$). These results suggest that the differences between single, first order and second order were not the result of speed-accuracy tradeoffs, since longer RTs were associated with higher error rates. Thus performance following CM training was both rapid and accurate. In contrast, performance in VM conditions remained sensitive to memory load following equivalent amounts of practice.

Single task tracking performance was evaluated by calculating RMS error for each condition and submitting this data to a three-way repeated measures ANOVA (subjects x sessions x system order). Subjects performed significantly better with first order dynamics than they did with second order dynamics ($F(1,6)=27.5$, $p<.01$, $MSe=27,343$). Subjects tracking performance also improved with practice ($F(1,6)=11.85$, $p<.01$, $MSe=4,706$). The interaction between system order and session was not significant.

Step-tracking performance in dual task conditions did not significantly differ from single task step-tracking conditions (all single/dual interaction $ps >.10$). These results suggest that subjects were successful

in maintaining single task tracking performance in the dual task conditions. Thus subjects apparently followed instructions and protected performance in the step-tracking (primary) task at the expense of the Sternberg (secondary) task.

Event-Related Potentials

The ERPs were recorded to address several issues. First, since the latency of the P300 component is influenced by the duration of stimulus evaluation processes but is relatively unaffected by response selection and execution processes, the joint use of RT and P300 latency were used to decompose the information processing demands of the Sternberg task as a function of task structure, practice and dual-task demands. Second, the amplitude of the P300 has been found to vary with the perceptual/cognitive demands of a task. Therefore, this measure was employed to provide an estimate of the resource costs of the tasks, both in isolation and when combined in the dual-task conditions.

Figure 13 shows the grand average ERPs, recorded at the parietal site,

 Insert Figure 13 About Here

for each of the single and dual task Sternberg conditions. ERP components are traditionally defined in terms of their latency relative to a stimulus or response, scalp distribution, and sensitivity to experimental manipulations (Donchin, 1981; Kramer, 1985; Sutton and Ruchkin, 1985). The large positive going deflection in the waveforms became increasingly positive from the Fz to the Pz electrode site ($F(2,12)=34.2$, $p<.01$) and the base to peak measures were maximal between 350 and 800 msec post-stimulus. Based on these criteria this positive deflection can be identified as the

P300.

After practice, the ERP complex became less variable in the CM condition, but not the VM condition. This is particularly true for the P300 component and appears to be the result of a reduction in the trial-to-trial latency jitter. Single trial analyses revealed that P300 amplitude was larger for target trials than for non-target trials ($F(1,6)=20.3$, $p<.01$, $MSe=79,474$), but did not change as a function of task structure, practice, memory load, or single/dual task conditions (all p 's $>.10$). Thus, except for the difference between target and non-target conditions, P300 amplitude was uninfluenced by any other experimental variables. These results are consistent with the hypothesis that attentional requirements of automatic and controlled processes are equivalent (i.e., automatic processes require attentional resources). However, since P300 amplitude was uninfluenced by the imposition and difficulty of the dual task, it suggests that the memory comparison process and the step-tracking task utilized separate resources. Similar conclusions were drawn in the discussion of the reaction time results and by Wickens (1980) review of a large number of dual task studies. If the memory comparison process used separate resources, subjects could have allocated these to the automatic process even though it was unnecessary (e.g., Schneider and Fisk, 1982b). However, in experiment 1 the two tasks utilized the same types of resources and large P300s were obtained. Given that P300 amplitude reflects the allocation of perceptual/cognitive processing resources, these results suggest that automatic processing requires attentional resources.

The mean P300 latency values obtained in each of the single task conditions are presented in Figure 14a. P300 latency occurred earlier for CM

Insert Figure 14 About Here

conditions than for VM conditions ($F(1,6)=9.6$, $p<.05$, $MSe=31,817$). P300 latency also decreased from session 1 to session 10 for CM conditions, but P300 latency remained relatively uninfluenced by practice in VM conditions ($F(1,6)=6.4$, $p<.05$, $MSe=8,316$). P300 latency increased as a function of memory load for VM targets both in session 1 and session 10. For target CM conditions, P300 latency increased from set size 2 to set size 3, but did not increase from set size 3 to set size 4 in session 1 and was unaffected by memory load in session 10 ($F(2,12)=3.91$, $p<.05$, $MSe=2571$). In addition, P300 latency was less influenced by memory load for non-target trials than for target trials.

The finding that the slope flattens out at the higher memory load conditions is consistent with Schneider's (1985) phase II stage of processing where both automatic and controlled processes co-occur. It is interesting to note that this effect did not become evident in RT until additional sessions of practice were provided. This suggests that P300 latency may be a more sensitive metric in the development of automaticity than overt measures of performance. Furthermore, given that P300 latency is influenced by stimulus evaluation processes, but is relatively insensitive to response related processes, it suggests that the component of the stimulus evaluation processing affected by memory load becomes automated prior to the components of the response related processing which are affected by memory load (cf. Ford et al., 1979). The differences in memory set effects between CM and VM conditions as a function of practice are

further supported by the linear regression slope and intercept parameters. Table 2 presents these values.

Insert Table 2 about here

Figure 14b and c presents the mean P300 latency values for the dual task conditions. The linear regression parameters for the dual task conditions are also presented in table 2. It is apparent from figure 14 that P300 latency increased with the imposition of the tracking task, but was relatively unaffected by changes in the difficulty of the tracking task. This effect is interesting because reaction time increased both from single task to first-order dual task conditions and from first-order to second-order dual task conditions. Thus the present data suggest that changes in the system order affect a response-related process, since latency was unaffected by changes in system order. Furthermore, the effects of memory load were approximately equivalent in single and dual task conditions. This suggests that the reduced set-size slope obtained with RT in the dual task second-order condition was the result of changes in the response-related component which were affected by memory load. These results suggest that the stimulus evaluation and response-related processes which are affected by memory load overlap (i.e., occur in parallel) in the second-order dual task conditions.

A comparison of RT and P300 latency revealed that the RT intercept decreased with practice for both CM and VM conditions, while only the CM P300 intercept decreased with practice. Following Sternberg's additive factors logic, this suggests that response-related improvements occur for both CM and VM conditions, but that encoding operations improve only for CM

conditions. A similar conclusion can be drawn by examining the difference in P300 latency between targets presented in the left or right side of the display. As figure 11 illustrates, there was no significant difference between display positions for CM targets; however, for VM conditions a significant difference between target positions was obtained. These results are in complete accord with the RT data and suggest that the extraction of perceptual information becomes more efficient following consistent practice.

A further examination of the RT and P300 latency intercept differences between single and dual task conditions suggests that the imposition of the dual task increases both encoding and response-related processing (i.e., both the RT and P300 latency intercepts increased, RT more so than P300 latency). However, changes in system order affected only response-related processing (i.e., only RT increased with system order).

The RT and P300 latency slope differences revealed that both stimulus evaluation and response-related processes were affected by memory load. There was no difference in the memory comparison process with the imposition of the dual task, suggesting that the imposition of the tracking task did not affect the memory comparison process. However, the second order tracking condition resulted in reduced slopes for RT, but not for P300 latency. This suggests that there was partial overlap in the components of memory search. The stimulus evaluation and response-related components of the memory search may be processed in parallel under this condition. It may be that the stimulus evaluation and response-related components of memory search overlap in all conditions, but was more pronounced in the second-order condition due to the increased response-related variance in this condition.

A single trial ratio of RT to P300 latency was computed to determine

the relative proportion of post-stimulus evaluation in each condition. The mean RT/P300 ratios for the experimental conditions are presented in figure 15. A referent value in the figure is the solid horizontal line drawn at the

 Insert Figure 15 About Here

RT/P300 ratio of 1.0. This ratio reflects the co-occurrence in time of the P300 peak latency and the RT response. Values larger than 1.0 reflect the condition where RT was preceded by P300 peak latency, whereas values less than 1.0 reflect the condition where P300 peak latency was preceded by RT.

The RT/P300 ratio was greater than or equal to 1.0 for both CM and VM conditions in session 1. However, in session 10 the RT/P300 ratio for the CM conditions was less than 1.0, while the ratio for the VM condition was greater than 1.0 at the larger set sizes. Thus in session 10, RT was shorter than P300 peak latency for all of the CM conditions for both single and dual tasks. It is important to note that the RT/P300 ratio decreased for both CM and VM conditions with practice ($F(1,6)=37.1$, $p<.01$, $MSe=4.72$). Furthermore, changes with practice were additive with memory load ($F(2,12)=0.67$, $p>.10$, $MSe=.0108$).

Taken together, these results suggest that less post-stimulus evaluation occurs after practice for both CM and VM conditions, because the RT/P300 ratio decreased for both conditions. This was due largely to a reduction in reaction time. Further, the data suggest that the extraction of perceptual information becomes more efficient following the development of automaticity. This follows because RT preceded P300 in these conditions and because the P300 intercept decreased with CM practice, but not VM practice. Further evidence was obtained by the comparison of target trials.

For CM conditions, there was no effect of target position on RT or P300 latency. In contrast, there were significant display effects for VM conditions. These results provide support for the model proposed by Salthouse and Somberg (1982). They hypothesized that one aspect of the acquisition of a skill is a qualitative shift in the type of information being processed. They speculated that "the encoded stimulus early in practice contains a relatively large number of stimulus components -- many that are relevant but also many that are irrelevant." Following consistent practice, "the irrelevant stimulus components are ignored and perhaps more useful components added" (p. 199). Laberge (1981) described this process as a within-system automatization. The present experiment suggests that this develops prior to the between-system automatization (i.e., the zero slope criterion).

Conclusions: Experiment 2

In sum, the present study found that P300 latency differentiated between CM and VM conditions earlier in training than reaction time. This suggests that P300 latency may be a more sensitive index of the development of automaticity than reaction time, and that stimulus evaluation processes may become automated more rapidly than response selection and execution processes. Furthermore, reaction time preceded P300 latency following CM training, but not VM training, suggesting that extraction of perceptual information becomes more efficient following the development of automaticity (see van Dellen et al., 1984 for a similar perspective). This finding was also supported by the comparison of differences in RT and P300 latency as a function of the position of the target in the display. If a CM target was presented, it was processed in parallel with other information in the display. In contrast, VM search required a serial attentional scan of the

icon. These changes developed rapidly with respect to changes in the memory set slope. A further finding of interest was the reduction in the intercept following practice for both CM and VM conditions. This was not accompanied by changes in the P300 latency intercept and suggests that the consistent aspects of the response process were also becoming automated with practice. Thus, consistency within any component in the processing sequence may lead to automatic processing of that process with practice.

The additivity of memory load and single/dual task effects suggests that the memory comparison process and the step-tracking task tapped different pools of attentional resources. Since neither RT nor the P300 latency slopes increased as a function of single/dual task conditions, it suggests that the step-tracking task did not interfere with the resources utilized by the memory search process. This conclusion is further supported by the P300 amplitude data, which were insensitive to changes in single/dual task conditions. The pattern of effects produced by changes in single/dual task conditions on RT and P300 latency suggest that the imposition of dual task conditions affects both an early encoding operation and a later response selection/execution stage, and that subsequent changes in system order affect only the later response selection/execution stages of processing.

Experiment 3: A Comparison of Process-Based and Memory-Based Theories

Experiment 3 contrasts two theories of automaticity: Process-based versus memory-based. Process-based theories assume that the set of operations used to perform a skill become more efficient following consistent practice. For example, Anderson (Neves and Anderson, 1981; Anderson, 1982; Anderson, 1983) described the acquisition of cognitive skills through a process of knowledge compilation. Initially, the knowledge

required to perform a skill is represented as a collection of facts which are stored in declarative memory. The declarative representations are operated upon interpretatively using a general set of productions. Knowledge representation at this level has the advantage of flexibility, but the cost of reduced speed.

With consistent practice, performance improves. This improvement is the result of knowledge compilation. The knowledge compilation process consists of two sub-processes. The first is proceduralization. Each time a production matches a representation in declarative memory the proceduralization mechanism creates a new procedure. This process reduces the demands placed on working memory.

The second component of knowledge compilation is a process of composition. Essentially composition involves the concatenation of procedures which are executed in a sequence into a single production. It is assumed that the time to perform a task is a function of the number of productions to perform the task. Thus the effect of composition is to reduce the time to perform the task.

Knowledge compilation has an advantage of speed, but a cost of reduced flexibility. Neves and Anderson (1981) describe how knowledge compilation accounts for the automaticity criteria. The zero slope criterion of automaticity is achieved by the composition of the serial comparison process into a parallel process. The reduced demands placed on working memory account for the time-sharing performance. Furthermore, productions are ballistic, which accounts for their autonomous behavior.

Thus according to Anderson, knowledge compilation is the mechanism responsible for the qualitative and quantitative changes in performance observed following consistent practice. It is important to note that the

cognitive operations used to perform the skill are not modified, rather the consistent aspects of a skill are concatenated to transform the multiple operation process into a single production. Similar views on the acquisition of skills have been proposed by Neuman, 1984; Newell, 1973; McLeod, McLaughlin, and Nimmo-Smith, 1985; and Fitts, 1964.

Memory-based theories of automaticity assume that automaticity is accomplished via a direct access retrieval from long term memory. For example, Logan (in press) proposed an instance theory of automaticity. According to this view the development of automaticity reflects a shift from the use of a generic set of cognitive operations (i.e., an algorithm) to the reliance on a direct access memory retrieval of past solutions. The model accounts for the power-function speedup in performance by a race between the algorithm and the memory retrieval process. Initially, the algorithm is more rapid and reliable and dominates performance. However, after multiple trials (which form multiple instances in memory), the retrieval process finishes prior to the algorithm and begins to dominate performance. This follows given that the minimum retrieval time decreases as the number of instances increase. The important difference between the memory-based and process-based theories is that memory-based theories do not assume that the algorithm is modified with practice (note that the algorithm can change with practice, but this is not the mechanism underlying automaticity). What changes, according to this view, is the knowledge gained from prior exposure, which permits the memory retrieval process to finish before the algorithm and thereby dominate performance.

Shiffrin and Schneider (1977; Schneider and Shiffrin, 1977; see also Schneider 1985) also proposed a memory-based theory. Unlike Logan's instance theory, Schneider's theory is a strength model. According to this view,

consistent practice serves to strengthen the Input/Output relationship, and this strengthening of the trace results in the power-function speedup in performance. In contrast, the varied mapping trials cancel out, resulting in a memory trace so weak that the algorithm finishes prior to the memory retrieval process. It should be mentioned that the present experiment is not attempting to differentiate between strength and instance based memory theories.

Memory-based and process-based theories of automaticity account for the changes in performance following consistent practice using different mechanisms. Process-based theories assume that the algorithm becomes more efficient, but that the same cognitive operations underlie behavior. Memory-based theories assume that a different cognitive operation (i.e., a direct memory retrieval of past solutions) is responsible for the changes in performance. One way to contrast memory-based and process-based theories would be to assess memory retrieval time for both automatic and non-automatic processing. If the retrieval time decreases with consistent practice, this would provide support for the memory-based theories. A technique for identifying memory retrieval time is described below.

The focus of experiment 3 is to contrast memory-based and process-based theories of automaticity by comparing the retrieval times in CM and VM conditions. A reduction in the retrieval time for CM conditions (relative to VM conditions) would provide support for memory-based theories. No difference between CM and VM memory retrieval time estimates would provide support for process-based theories of automaticity.

Several studies have compared performance in memory search tasks when the memorized items are either in primary or secondary memory (see footnote 1). The focus of these studies is on the dynamics of the process of

retrieval of information from secondary memory to primary memory. Using additive factors (Sternberg, 1969b) and subtraction (Donders, 1868/1969) logic, one can make inferences about the processes which are involved in the transfer of information and the relative duration of these processes. This can be achieved by comparing the regression equation parameters of performance in primary and secondary memory. Differences in the intercepts and slopes of primary and secondary memory reveal the characteristics of this transfer process. Typically these experiments employ a distractor task between the presentation of the memory set and the probe stimulus to prevent rehearsal of the memory set items. Without rehearsal, information in primary memory decays rapidly (e.g., Peterson and Peterson, 1959, Murdock, 1961; Muter, 1980), thus the information must be retrieved from secondary memory for subjects to perform the memory search task.

Sternberg (Sternberg, 1969a, Exp. 5, Sternberg, Kroll, and Nasto, 1969; Sternberg, 1970) was one of the first to compare primary and secondary memory performance in the memory search task. Subjects memorized a list of 1, 3, or 5 digits. In the secondary memory condition, a list of 7 letters was sequentially presented (with a total duration of 3.5 seconds) prior to the presentation of the probe stimulus. Subjects were instructed to retain the list of letters in memory, and catch trials were included to insure that subjects complied with instructions. The retention of the list of letters was intended to prevent subjects from rehearsing the memory set and require the retrieval of the memory set from secondary memory. In the primary memory condition, no distractor task preceded the probe stimulus. The linear regression equation for primary memory was $RT = 336 + 57(x)$, while for secondary memory $RT = 467 + 105(x)$, where x refers to memory set size. Both the intercept and the slope were greater for the secondary memory condition.

The increase in the intercept (131 msec) was taken to reflect the time to locate the memory set in secondary memory. The increase in the slope (57 msec) was taken to suggest a serial transfer of the entire memory set into primary memory. One caveat in interpreting the differences between primary and secondary memory in these studies concerns the duration of the distractor task. Evidence from the Brown-Peterson paradigm suggests that the memory set information may not have completely decayed from primary memory within the 3.5 second interval (see Flexser, 1978 for a similar argument). If this were the case, the increase in the slope from primary memory to secondary memory may be the result of a mixture of primary and secondary memory performance, and thus the slope differences are ambiguous. Furthermore, if the memory set information had not fully decayed from primary memory, the difference between primary and secondary memory would underestimate the true retrieval time.

Wickens and colleagues (Wickens, Moody, and Dow, 1981; Wickens Moody, and Vidulich, 1985) have provided the most extensive studies comparing primary and secondary memory. Wickens et al., (1981, exp. 1), presented memory sets of 2 or 4 words for 3 seconds. Following the memory set, subjects were presented with a random three digit number and instructed to count backwards by 3s for a duration of 12 seconds. A 2 second interval in which the random number was removed from the display signaled the end of the distractor task and the upcoming probe stimulus. No measure of subjects performance was obtained for the distractor task. The probe was presented for 2 seconds, and the interval in which subjects could respond was 3 seconds from probe onset. A manipulation investigating the effects of proactive interference on primary and secondary memory was accomplished by selecting the words in the memory set from the same taxonomic category.

Three trials using stimuli from the same taxonomic category were presented (without repetition of words) before a new category was chosen. The first memory set was deemed low in interference, the third high in interference. Experimental factors were mixed within the session. Wickens et al., (1981, exp. 2) was identical to Wickens et al., (1981, exp. 1), with the exception that the distractor task was eliminated. This constituted the primary memory condition. Note that the primary - secondary memory manipulation was a between subjects factor. Thus comparisons between experiments 1 and 2 provide a measure of the time to transfer the memory set from secondary memory to primary memory.

The slopes and intercepts obtained in the experiment are:

	Primary	Secondary
target	$RT = 500 + 33(x)$	$RT = 595 + 39(x)$
non-target	$RT = 501 + 36.25(x)$	$RT = 630 + 37.5(x)$

It is evident that memory load did not interact with the manipulation of primary and secondary memory, which is in contrast to Sternberg's (1969a, exp. 5) results. One potential reason for the discrepancy is the nature and duration of the distractor task. The Wickens study prevents subjects from rehearsing the memory set for a longer duration than Sternberg's studies, and probably reflects a more accurate representation of secondary memory performance. It is also apparent that there is a substantial difference in the intercepts of primary and secondary memory (112 msec). This estimate is more closely in agreement with the Sternberg studies.

The data from experiments 1 and 2 were fitted to the following regression equation:

$$RT = [a + b(x) + t] + [(r1 + r2) + q]$$

The first bracketed term in the equation describes performance in primary

memory, where " a " refers to the intercept, " b " refers to the slope, " x " refers to memory set size, and " t " refers to differences between target and non-target stimuli. The second bracketed term describes performance in secondary memory. The term " r1 " refers to the increase in the intercept under low proactive interference conditions, " r2 " refers to the additional increase under high proactive interference conditions, and " q " refers to differential effects for target and non-target stimuli. The values for the terms in the equation are:

$$RT = [489 + 37(x) + 14] + [(95 + 38) + 17]$$

This model accounted for 99% of the variance across conditions. It is important to note that these results imply that the retrieval process is independent (but see Sternberg, 1969b) of the memory search process. According to this interpretation, there is a constant time for retrieving the memory set items, and they are retrieved in a chunk (i.e., in parallel). Furthermore, the effects of memory load produced equivalent results, suggesting that the memory search process is the same for items in primary memory as for items which have to be transferred from secondary memory to primary memory.

Wickens (Wickens et al., 1985, expl; Wickens, personal communication, March 12, 1987) has also demonstrated the independence of memory search rate and memory retrieval time using both out of category non-target probes and repeated stimuli. Both effects reduced the slope, but the primary - secondary memory differences were maintained. Flexser (1978) has also reported similar intercept differences between primary and secondary memory using memory sets of 16 and 32 (which produced small effects on search time). These results offer additional support for the assertion that the retrieval process and the memory search process are independent. Wickens

concluded that secondary memory conditions differ from primary memory conditions in the addition of a retrieval process inserted prior to the memory search operation.

In sum, the studies which have compared primary and secondary memory using memory search paradigms have universally found that there is an increase in the intercept between primary and secondary memory. The magnitude of this effect seems to vary with the type of material -- words produce a larger effect than letters or digits (e.g., Wickens et al., 1985, exp. 2). Furthermore, there is some evidence that the magnitude of the difference between primary and secondary memory is dependent on the strength of the trace in primary memory. The longer the interval between the memory set and the probe stimulus, the greater the difference between primary and secondary memory. This difference in the intercept between primary and secondary memory has been interpreted as the time to retrieve the information from secondary memory.

The effect of memory load on primary and secondary memory has produced mixed results. The majority of studies report parallel curves for primary and secondary memory (Wickens et al., 1981; Wickens et al., 1985; Wickens, personal communication, 1987; Flexser, 1978). Forrin and Morin (1969) reported shallower slopes for the secondary memory condition, but subjects received substantially more practice (i.e., consistent practice) in the secondary memory condition than in the primary memory condition. A few studies have reported steeper slopes for secondary memory conditions (e.g., Sternberg, 1969, 1970; Sternberg, Kroll, and Nasto, 1969; Peters, 1974). However, in these studies the interval between the memory set and the probe stimulus was such that it is questionable whether the memory set information had decayed from primary memory. If one assumes that rehearsal strengthens

the trace in primary memory, as set size increases the average trace strength of each memory set item should decrease. This would result in differential decay rates for different memory set sizes. Smaller memory set sizes should take longer to decay, since the rehearsal cycle time varies with memory load (e.g., Baddeley and Ecob, 1973; Cavanaugh, 1972; Clifton and Birenbaum, 1970; Corballis, Kirby, and Miller, 1972; Monsell, 1978). This would produce a greater proportion of primary memory trials following a short distractor task for smaller set sizes than for larger memory set sizes. The expected outcome would result in a steeper slope for this mixture condition than for a pure primary memory or a pure secondary memory condition.

An important consideration when evaluating the differences between the studies concerns the nature of the distractor task. The distractor tasks varied in difficulty and duration, and none of the experiments objectively evaluated subjects performance in the distractor task. The most effective distractor tasks employed a backwards count task for a duration of at least 12 seconds. All of these studies reported parallel memory load functions for primary and secondary memory. However, since performance in the distractor task was not monitored, it is possible that subjects may have rehearsed the memory set even in these conditions. Clearly a distractor task in which performance can be monitored over the course of the distractor interval is warranted.

A final issue concerns the interval between when the distractor task was terminated and when the probe stimulus was presented. This duration varied from 500 msec to 2 seconds in the studies reviewed above. It is unclear what subjects were doing in this interval, and why they did not transfer the memory set information from secondary to primary memory. Given

the estimates of retrieval time, subjects should have had ample time to complete this operation prior to the presentation of the probe stimulus. Upon post-experimental questioning, subjects reported that they did not retrieve the memory set information prior to the presentation of the probe stimulus (Wickens et al., 1985). If subjects had, in fact, retrieved any information from secondary memory, this should tend to obscure any true differences between primary and secondary memory.

Experiment 3a: Primary/Secondary Memory Search

Several methodological and interpretative issues remain which need to be addressed before this paradigm can be used to assess differences in retrieval times for automatic and controlled processing. The purpose of experiment 3a was to address these issues and provide additional information concerning the process of retrieval of information from secondary memory to primary memory.

One issue to be addressed is the proposition that the retrieval process is independent from the memory search process. There was a trend in the literature for studies using short distractor intervals (e.g., 4 seconds) to find larger slopes for secondary memory conditions, while studies which used longer distractor intervals (e.g., 12 seconds) found equivalent slopes for primary and secondary memory. The present experiment will evaluate the contribution of the duration of the distractor interval on the additivity of the retrieval and memory comparison processes by manipulating the delay between the memory set and the presentation of the probe stimulus. Three delay conditions will be included: 0, 4, and 15. The 0 delay condition represents the situation in which no distractor task is presented between the memory set and the probe (i.e., a pure primary memory condition). In the 4 second delay condition, subjects will perform a distractor task for 4

seconds prior to the presentation of the probe stimulus. The duration of the distractor task in this condition is quite close to the parameters of Sternberg's experiment in which an increase in the set size slope was observed compared to primary memory. In the 15 second delay condition, subjects will perform a distractor task for 15 seconds prior to the presentation of the probe. This condition is roughly equivalent to that employed in the Wickens studies, and is intended to represent a condition in which the memory set information is not in primary memory (i.e., a pure secondary memory condition). Following additive factors logic, if the memory retrieval process is independent of the memory search process, then the effects of delay should be additive with the effects of memory load.

A second issue to be addressed by this research is related to the finding in the Wickens study that subjects apparently did not retrieve the memory set until the probe was presented, even though they were cued to stop the distractor task and prepare for the probe trial with a 2 second warning interval. It is unclear why subjects did not retrieve the memory set during this interval. If subjects retrieved any information prior to the presentation of the probe stimulus, the estimates of retrieval time represent an underestimate of the true retrieval time. The present study will present a retrieval cue which signals the termination of the distractor task (if presented). The probe stimulus will be presented at three stimulus onset asynchronies (SOAs) following retrieval cue onset: 200, 500, and 1000 msec. If subjects are retrieving any of the memory set information prior to the presentation of the probe, then the retrieval time estimate (the intercept difference between primary and secondary memory) should diminish as SOA increases. The three SOA conditions will be factorially combined with the three delay conditions. Two memory set sizes will be presented: 2

and 4 and target and non-target trials will be equiprobable. All conditions will be mixed to reduce changes in bias between conditions. It is predicted that reaction time will increase as a function of delay and that this increase reflects the time to retrieve the memory set information from secondary memory. It is also predicted that if the transfer of the memory set information is parallel, as suggested by Wickens, then the slopes for the 0 and 15 msec delay conditions should be equivalent. If performance in the 4 msec delay condition reflects a mixture of primary and secondary memory conditions and this proportion varies with memory load, then there should be an increase in the slope for this condition relative to the 0 and 15 msec delay conditions. These effects should be modulated by SOA. The largest differences between delay conditions should be observed with the shortest SOA condition. If subjects retrieve any information prior to the presentation of the probe stimulus, the difference between delay conditions should decrease as SOA increases.

Methods: Experiment 3a

Subjects

Ten subjects (3 female), age 18 to 25 participated in experiment 3a. Each subject participated in 6 one hour sessions. Subjects were paid for their participation.

Stimuli

The stimuli presented in the Sternberg portion of the experiment were 4 letter, monosyllabic, nouns with a word frequency of 70 to 148 (Kucera, Henry, Francis, and Nelson, 1967). Words were selected so as not to rhyme or have orthographic similarity. A further constraint used in stimulus selection was to examine all possible word pairs and eliminate any words which resulted in strong natural associations. Thus the words formed a

heterogeneous class of stimuli. Table 3 presents the word-list employed in the experiment. The approximate visual angle of the words subtended 1.2 degrees horizontally and 0.5 degrees vertically.

 Insert Table 3 about here

The stimuli used in the recognition running memory portion of the experiment were the digits 1 to 9. Digits were selected randomly. The approximate visual angle of the running memory stimuli subtended 0.3 degrees horizontally and 0.5 degrees vertically.

Apparatus

The experiment was performed on an IBM XT, with a quadEGA card which permitted cursor control and synchronization. The stimuli were displayed on an IBM monochrome display. Subjects indicated their responses by pressing the "Z" key with the left index finger and the "/" key with the right index finger on the keyboard of the IBM computer.

Procedure

Each trial was comprised of the following events. A memory set was presented for a duration of 3000 msec. This was followed by a 1500 msec interval in which the display was blanked. Three delay intervals followed the memory set: 0, 4, and 15 seconds. During the delay interval, subjects performed a recognition running memory task which prevented rehearsal of the memory set. Following the delay interval, an asterisk was presented for 200 msec which served as a cue for subjects to retrieve the memory set information. Three stimulus onset asynchronies (SOAs) were included between onset of the retrieval cue and the onset of the Sternberg probe stimulus: 200, 500, and 1000 msec. The Sternberg probe was presented for 200 msec and

legal reaction times were permitted within a 3000 msec interval following probe onset.

Sternberg memory set sizes of 2 and 4 words were used in the experiment. Target and non-target trials were presented equiprobably. Targets were defined as items from the memory set, non-targets were items not included in the memory set. Subjects pressed one key for target trials and another key for non-target trials. Key assignments were counterbalanced across subjects. Instructions emphasized both speed and accuracy.

The recognition running memory task was identical to Experiment 1, with the following exceptions. An interval of 1000 msec separated running memory stimuli. Digits were chosen randomly, with the constraint that mismatch stimuli occurred twice as often as match stimuli. This constraint was introduced to keep the difficulty of the running memory task constant across trials. Subjects were given 1000 msec to indicate their response. Instructions emphasized both speed and accuracy. It should be re-emphasized that subjects found the running memory task extremely demanding, requiring all their effort to maintain performance in the task. While subjects performed the running memory task, they were instructed not to rehearse or otherwise think about the memory set items. Performance in the running memory task provided a good index of subjects compliance to these instructions (see footnote 2).

Design

Memory set sizes of 2 and 4 were presented, with target and non-target trials equiprobable. Three delay conditions were included: 0, 4, and 15 seconds. During the delay, subjects performed the recognition running memory task, which served to prevent subjects from rehearsing the memory set. In addition, three SOAs between retrieval cue onset and probe stimulus

onset were employed: 200, 500, and 1000 msec. Conditions were factorially combined to form a 2 (memory load) X 2 (target vs non-target) X 3 (delay) X 3 (SOA) design. Conditions were randomly permuted across sessions and subjects. Subjects participated in all experimental conditions. A total of 36 observations per cell were obtained for each subject. The first session of the experiment served as practice and was not included in the analyses.

Results and Discussion: Experiment 3a.

Figure 16 presents the mean reaction times obtained in the Sternberg task. Only trials in which subjects were correct are included. An additional constraint employed in selecting trials for analysis omitted trials in which performance in the running memory task (if presented) was below chance accuracy. Data are plotted separately for target and non-target

Insert Figure 16 About Here

trials and for different SOA conditions. Line segments connect memory set size means within a condition. Several effects are noteworthy. First, reaction time increased as a function of memory load in all conditions, $F(1,9)=36.56$, $p<.001$, $MSe=628,672$. Memory load did not interact with any other variables (all $ps > .10$), suggesting that the memory search process did not differ between tasks. This conclusion is born out by the linear regression slopes fitted to each of the conditions in the experiment. The average slope in the experiment was 42.0 msec per item. A comparison of the 0 and 15 second delay conditions replicates the effects reported by Wickens. The hypothesis that the difference in slopes between primary and secondary memory reported by Sternberg was due to the difference in the duration of the distractor task was rejected. This follows given the equivalence of the

slopes across all delay conditions. Furthermore, these data are consistent with a model in which the retrieval process is independent of the memory search process, since memory load did not interact with delay.

A second noteworthy aspect of the data is the effect of SOA on reaction time. There was a general trend for reaction time to decrease as SOA increased, $F(2,18)=62.93$, $p<.001$, $MSe=503,925$. We interpret this change as a non-specific warning effect. The greater the time between the onset of the retrieval cue and the onset of the probe, the more subjects prepared for the upcoming probe. This effect was non-monotonic, with the greatest effect obtained between the 200 and 500 msec SOA conditions (67 msec), and a lesser effect between the 500 and 1000 msec SOA conditions (42 msec).

The manipulation of delay produced large differences in performance. As delay increased, reaction time increased, $F(2,18)=18.26$, $p<.001$, $MSe=1,677,965$. This effect produced changes in the linear regression intercept, but not the slope. Following Sternberg's additive factors logic, the additivity suggests that the delay and memory loads affect different processes. The former presumably affects a retrieval process, while the latter affects a memory search process.

The effect of delay was modulated by SOA, $F(4,36)=9.81$, $p<.001$, $MSe=35,246$. As SOA increased, the effect of delay decreased. However, this reduction in reaction time occurred largely between the 0 and 4 second delay conditions, while the difference between the 4 and 15 second delay conditions remained constant across SOA conditions. The difference between the 0 and 15 second delay conditions was approximately 285 msec in the 200 msec SOA condition. This decreased to approximately 175 msec in the 1000 msec SOA condition.

The difference in delay conditions has been used to infer the duration

of the retrieval process. Since the magnitude of the effect of delay decreases as SOA increases, it suggests that part of the memory set information is retrieved during the SOA interval. It is unclear why subjects retrieved only part of the information during the SOA interval. Given the estimate of retrieval time (275 msec) and the time to process the retrieval cue (upperbound estimate of 300 msec from simple RT tasks), subjects should have been able to retrieve the memory set information within 600 msec. Thus subjects are not fully capitalizing on the SOA interval.

One reason that reaction time differed as a function of delay in the 1000 msec SOA condition might be that this condition represents a mixture of primary and secondary memory trials. On some trials, the memory set information may be retrieved, while in others the retrieval may not have been completed. If the proportion of primary memory trials to secondary memory trials increased as SOA increased, the effect of delay should diminish as SOA increases. This is precisely what is observed. If this hypothesis is correct, then the 1000 msec SOA reaction time distribution should represent a mixture of pure primary and pure secondary memory trials.

To address the mixture hypothesis, the reaction time distributions for each subject and each condition were vincentized (Vincent, 1912; Ratcliff, 1979) to form a composite cumulative frequency distribution (CFD). The vincentizing procedure is described in detail by Ratcliff (1979). Briefly, the reaction times for each subject and condition are sorted into ascending order and the quantiles are calculated. The quantiles are then averaged across subjects to obtain the group quantiles. From the group quantiles a group reaction time distribution is generated which retains the shape of the individual subject distributions. This process is equivalent to a simple linear interpolation, and the resulting distribution represents the

distribution of the average subject. The CFDs have been divided into 20 intervals, each containing 5% of the distribution. The mean of each interval is cross-plotted against the interval position.

The CFDs for the 0 and 15 second delays are plotted at each SOA for target memory load 4 trials in figure 17. All the CFDs have a general

 Insert Figure 17 About Here

scallop shape which reflects a positive skew in the RT distributions. Of central interest is the shape of the distributions for the different delays as a function of SOA. For the 0 delay condition, the CFDs are tightly clustered and parallel over the entire latency interval. Each distribution is shifted with SOA. The CFDs for the 15 second delay conditions are also plotted in the figure. For the 200 msec SOA condition the entire CFD has shifted out in time relative to the 0 delay CFDs. In contrast, the 500 and 1000 msec SOA conditions produced CFDs which initially clustered with the 0 delay conditions. At about the median of each CFD, the functions deviate from the 0 delay conditions and approach the 15 second delay 200 msec SOA condition. This reflects a mixture of distributions (Ratcliff, 1979) and supports the hypothesis that the 1000 and 500 msec SOA conditions reflect a mixture of primary and secondary memory trials. Furthermore, if subjects are retrieving memory set information in the SOA interval, one would predict that the proportion of primary memory trials would be larger in the 1000 msec SOA condition. This in fact appears to be the case. The CFD for the 500 msec SOA condition deviates from the 0 delay conditions more rapidly than does the 1000 msec SOA condition. Thus, these data suggest that subjects are retrieving information about the memory set during the SOA

interval and that performance at longer SOAs reflects a mixture of primary and secondary memory trials. The proportion of primary to secondary memory trials is modulated by the SOA interval.

To estimate the proportion of primary and secondary memory trials in the 1000 msec SOA, 15 second delay condition, hypothetical distributions were generated by randomly selecting trials from the 0 and 15 second delay 200 msec SOA conditions. Figure 18 presents the CFDs for selected proportions of primary and secondary memory trials. The CFD obtained in the

 Insert Figure 18 About Here

1000 msec SOA, 15 second delay condition (adjusted for SOA) is also plotted in figure 20. This condition falls between the 50/50 and 75/25 secondary/primary memory proportions and provides further support for the mixture hypothesis.

One effect which did not attain significance was the effect of response type (target vs non-target), $F(1,9)=3.06$, $p>.10$, $MSe=272,580$. This is consistent with previous research in which the memory set is changed after every trial (Sternberg, 1975). Further, the probability of a mismatch trial was twice the probability of a match trial in the running memory task and this may have offset any response bias for target trials in the Sternberg task.

Conclusions: Experiment 3a

In sum, the additive effects of memory load and delay provide support for the interpretation of separate retrieval and memory search processes. The data further suggest that the memory set information is retrieved as a unit. These results are in direct contrast to Sternberg's findings. The

data from the 4 second delay condition suggest that the duration of the distractor task was not responsible for these differences. The manipulation of SOA provided evidence that subjects retrieve some of the information during the SOA interval; however this retrieval is not complete prior to the presentation of the probe. The 1000 msec SOA condition should have provided ample time to retrieve the information. Evidence from the distributions of reaction time for the different conditions suggest that performance in the 1000 msec SOA condition may represent a mixture of primary and secondary memory conditions.

Experiment 3a examined several issues which needed to be resolved before this paradigm could be used to examine the retrieval times of automatic and controlled processing. These issues have been addressed -- the duration of the distractor task did not result in different memory set-size slopes and subjects do retrieve the memory set on some trials prior to the presentation of the probe stimulus. We now propose an experiment which uses the methodology of experiment 3a to contrast process-based and memory-based theories of automaticity.

Experiment 3b: Retrieval Times for Automatic and Controlled Processing

The purpose of experiment 3b is to contrast process-based and memory-based theories of automaticity using the primary - secondary memory paradigm employed in experiment 3a. Process oriented views of automaticity (e.g., Anderson, 1982) assume that the cognitive operations become more efficient following consistent practice. Memory oriented views of automaticity (e.g., Logan, in press, Schneider, 1985) assume that automatic processes are the result of a direct access memory retrieval operation. Following the development of automaticity, performance is governed by the retrieval of information from memory and not by the initial cognitive

operations set up early in performance (i.e., the algorithm). These two views are not necessarily mutually exclusive, although either may be sufficient for the qualitative changes in performance observed following consistent practice(cf. Salthouse and Somberg, 1982).

The two theories of automaticity make differential predictions regarding the retrieval of information from secondary memory. Memory based theories assume that the performance changes following automaticity are the result of a direct memory access. Therefore memory based theories predict that the differences in performance as a function delay should be maintained for VM conditions, but that there should be little or no effect of delay following consistent practice. If automated performance in primary memory is governed by a direct access retrieval process, then it should not matter if the information is or is not in primary memory. That is, whether or not the information is in primary memory, performance should be based on a direct memory retrieval operation following consistent practice. Thus memory-based theories predict that the change in the intercept as a function of delay should be reduced or eliminated under CM conditions, and should be retained under VM conditions.

In contrast, process-oriented theories of automaticity assume that the algorithm changes as a function of practice. However, the operations are still carried out in primary memory. Thus process-oriented theories of automaticity predict that there should be no difference in retrieval time for CM and VM conditions. That is, the information must still be retrieved from secondary memory before the process can operate on it and this should result in an increase in the intercept as a function of delay. These predictions will be contrasted using the primary-secondary memory paradigm employed in experiment 3a. Both CM and VM variants of the Sternberg task

will be included.

A second issue to be addressed by experiment 3b is an examination of the development of the properties of automaticity. Specifically, this experiment will provide a comparison of the changes in memory search rate with consistent practice as a function of the difference between primary and secondary memory. If the difference between primary and secondary memory is reduced or eliminated following consistent practice, will this property co-occur with the reduction of the slope function? Memory based theories of automaticity predict that these two properties should co-occur. According to this view, the set size reduction is mediated by the retrieval of information from secondary memory. Thus the difference between primary and secondary memory should diminish as the set size slope diminishes. Presumably the slope reduction reflects a mixture of controlled and automatic (direct access memory retrieval) processing. As the proportion of direct access trials increases, the difference between primary and secondary memory should diminish. Process oriented views of automaticity hold that the algorithm becomes more efficient following practice. However, in secondary memory conditions the memory set information must be retrieved prior to the search. Thus process oriented views predict a reduction of the memory set size function without a concomitant reduction in the retrieval time.

Methods: Experiment 3b

Subjects

Sixteen subjects will be recruited to participate in the experiment. Subjects will be right handed, age 18 to 25. Half the subjects will participate in a CM variant of experiment 3a, while the remaining subjects will participate in a VM variant of experiment 3a. Subjects will be paid for

their participation.

Stimuli and Apparatus

The same stimuli and apparatus from experiment 3a will be employed in the present experiment. Ten words will be randomly selected from the wordlist used in experiment 3a. For subjects in CM conditions, 5 words will be selected to form the CM target ensemble and 5 words will be used to form the CM non-target ensemble. For VM conditions, 10 words will be selected. On each trial half of the words will form the VM target ensemble and half the words will form the VM non-target ensemble. The assignment of words to the CM and VM lists will be randomized across subjects.

Procedure

The procedure will be similar to experiment 3a, with the exception that half the subjects will receive CM training and the remaining subjects will receive VM training (in experiment 3a, subjects received VM training only). An additional modification from experiment 3a will be that on every other block of trials, only the 0 delay condition (i.e., the primary memory condition) will be presented. This is intended to increase the rate of development of automaticity for subjects in the CM condition. This manipulation will be employed for both subjects in CM and VM conditions to equate for the amount of practice.

Design

The design will be similar to experiment 3a, with the exception that a new factor, stimulus-response mapping, will be added. This factor will be a between subject factor. In addition, the 500 msec SOA condition will be omitted. All experimental conditions will be factorially combined to form a 2 (CM or VM) x 2 (memory load 2 or 4) x 2 (target or non-target) x 2 (SOA: 200 or 1000) x 3 (Delay: 0, 4, or 15) design. All within subject conditions

will be counterbalanced across sessions. The first day in the experiment will serve as practice. For all subjects, this first day of practice will incorporate VM training. This is intended to permit practice in the primary - secondary memory task prior to any CM practice and should permit a separation of non-specific improvement in the primary-secondary memory task with specific improvement due to consistent mapping.

The primary memory only conditions will form a 2 (set size) x 2 (response type) x 2 (SOA) design. Table 4 presents the structure of the experiment for each day. This design will result in 504 trials per day. Twelve days of practice will be provided which will result in 6048 total trials. Nine observations per day will be obtained for each cell in the full design.

 Insert Table 4 about here

Predicted Outcomes and Interpretations: Experiment 3b

Figure 19 presents five hypothetical outcomes of the experiment. The

 Insert Figure 19 About Here

predicted effects of SOA are present in the left (200 msec SOA) and right (1000 msec SOA) columns. The top row of the figure presents the expected outcome for VM conditions. This condition represents a partial replication of experiment 3a. Rows two through 5 present hypothetical outcomes in the CM variant of the experiment. Row two presents a case in which the zero slope criterion is achieved, but the intercept difference between primary and secondary memory is equivalent to VM conditions. This result would

support the process-oriented view of automaticity. The third row presents a partial reduction in the intercept conditions for CM conditions, relative to VM conditions, but some intercept difference remains. This result would provide evidence which supports both theories of automaticity. Some of the reduction in memory search time is accompanied by a reduction in retrieval time, but some retrieval time remains between primary and secondary memory condition. By examining the temporal relation of the reductions in slope and retrieval time, one can infer if the reduction in the slope is partially the result of a direct memory retrieval process. The fourth outcome, presented in row 4, represents the case where some intercept difference remains in the 200 msec SOA condition, but the difference is eliminated in the 1000 msec SOA condition. This result would suggest that some, but not all, of the reduction in the slope is accomplished by a direct memory retrieval process. Perhaps the slope in the CM condition may be modulated by the SOA, and if this is the case, it would provide support for memory-based theories of automaticity. Row five presents the final outcome depicted in the figure. Here the difference between primary and secondary memory is absent for both SOA conditions. These results would provide strong support for the memory-based theories, for it would suggest that automaticity is the result of a retrieval of information from secondary memory.

An additional issue to be examined concerns whether or not the slope reduction in the CM condition will there be accompanied by a concomitant decrease in the reduction of the intercept difference between primary and secondary memory conditions. If so, will the slope change lag, lead, or co-occur with the reduction in the intercept as a function of delay? If the development of automaticity, as indexed by the reduction of the slope, is

the result of a direct memory access process, as suggested by memory oriented views, then the processes should co-occur. That is, the two should be indices of the same process -- a direct memory access. This would provide a new criterion for automaticity -- the lack of an effect of memory retrieval time (as indexed by intercept differences between primary and secondary memory conditions) following consistent practice.

Footnotes

Footnote 1. The terms primary and secondary memory originate with William James (1890, p. 646-648). Contemporary treatments can be found by Waugh and Norman (1965) Craik and Levey (1976), Atkinson and Shiffrin (1968), Baddeley and Hitch (1974), and Baddeley (1981). According to James, primary memory reflects the contents of consciousness, while secondary memory refers to information that no longer is in consciousness. Following Waugh and Norman (1965) primary memory can be defined in terms of its limited capacity and the rapid decay of information if rehearsal is not permitted. Rehearsal serves to maintain information in primary memory and transfer the information to secondary memory. Secondary memory is characterized as a large capacity storage system with a low forgetting rate.

Footnote 2. Care was employed selecting the words so as not to form any obvious categories and subjects were instructed not to use elaborative/chunking strategies when memorizing the memory set. These manipulations were intended to minimize any effectiveness of the compression of the memory set into subgroups of categories. Furthermore, since this was a VM task, it would be quite difficult for subjects to form associations for every pairwise and four-way comparison.

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Table 1

Reaction Time Linear Regression Parameters

				Intercept	Slope	Corr
Single task sess 1	CM	Targets	444	43.1	0.43	
Single task sess 1	CM	Non-Targets	533	39.6	0.42	
Single task sess 10	CM	Targets	454	1.3	0.02	
Single task sess 10	CM	Non-Targets	496	2.1	0.03	
Single task sess 1	VM	Targets	474	53.6	0.55	
Single task sess 1	VM	Non-Targets	503	71.5	0.58	
Single task sess 10	VM	Targets	404	52.6	0.51	
Single task sess 10	VM	Non-Targets	407	72.2	0.53	
<hr/>						
First-order sess 1	CM	Targets	494	28.5	0.31	
First-order sess 1	CM	Non-Targets	544	40.4	0.39	
First-order sess 10	CM	Targets	450	10.7	0.18	
First-order sess 10	CM	Non-Targets	504	5.3	0.07	
First-order sess 1	VM	Targets	483	56.6	0.50	
First-order sess 1	VM	Non-Targets	536	67.6	0.53	
First-order sess 10	VM	Targets	415	50.6	0.57	
First-order sess 10	VM	Non-Targets	429	63.5	0.65	
<hr/>						
Second-order sess 1	CM	Targets	564	15.3	0.15	
Second-order sess 1	CM	Non-Targets	651	17.2	0.17	
Second-order sess 10	CM	Targets	507	0.1	0.00	
Second-order sess 10	CM	Non-Targets	524	8.1	0.07	
Second-order sess 1	VM	Targets	574	33.3	0.28	
Second-order sess 1	VM	Non-Targets	668	28.0	0.24	
Second-order sess 10	VM	Targets	463	42.1	0.35	
Second-order sess 10	VM	Non-Targets	501	49.4	0.37	

Table 2
P300 Latency Linear Regression Parameters

				Intercept	Slope	Corr
Single task sess 1	CM	Targets	513	14.6	0.20	
Single task sess 1	CM	Non-Targets	605	2.0	0.02	
Single task sess 10	CM	Targets	538	0.3	0.00	
Single task sess 10	CM	Non-Targets	557	13.7	0.12	
Single task sess 1	VM	Targets	503	27.2	0.35	
Single task sess 1	VM	Non-Targets	647	-12.4	-0.12	
Single task sess 10	VM	Targets	525	22.6	0.31	
Single task sess 10	VM	Non-Targets	598	9.5	0.10	
<hr/>						
First-order sess 1	CM	Targets	513	23.9	0.34	
First-order sess 1	CM	Non-Targets	659	-9.1	-0.12	
First-order sess 10	CM	Targets	535	9.7	0.11	
First-order sess 10	CM	Non-Targets	604	6.4	0.07	
First-order sess 1	VM	Targets	534	25.1	0.36	
First-order sess 1	VM	Non-Targets	610	6.6	0.11	
First-order sess 10	VM	Targets	589	12.6	0.15	
First-order sess 10	VM	Non-Targets	622	13.3	0.14	
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Second-order sess 1	CM	Targets	531	20.4	0.31	
Second-order sess 1	CM	Non-Targets	647	-2.2	-0.03	
Second-order sess 10	CM	Targets	587	-10.4	-0.18	
Second-order sess 10	CM	Non-Targets	583	14.1	0.18	
Second-order sess 1	VM	Targets	534	25.1	0.36	
Second-order sess 1	VM	Non-Targets	610	6.6	0.11	
Second-order sess 10	VM	Targets	537	22.8	0.34	
Second-order sess 10	VM	Non-Targets	599	19.3	0.26	

Table 3

BANK	BASE	CAMP
CLAY	CLUB	DATE
DEAL	DUST	EDGE
FARM	FILE	GAME
HAIR	HEAT	HOUR
MARK	NOTE	RAIN
ROCK	ROSE	RULE
SHIP	SIGN	SIZE
STEP	TERM	TEST
TONE	WINE	WISH

Table 4

Experimental design for day 1 of practice (VM training)

12 replications of the primary memory only conditions (96 trials)
3 replications of the complete design (72 trials)
12 replications of the primary memory only conditions (96 trials)
3 replications of the complete design (72 trials)
12 replications of the primary memory only conditions (96 trials)
** 3 replications of the complete design (72 trials) (CM or VM) **

Experimental design for days 2 - 13 of practice

12 replications of the primary memory only conditions (96 trials)
3 replications of the complete design (72 trials)
12 replications of the primary memory only conditions (96 trials)
3 replications of the complete design (72 trials)
12 replications of the primary memory only conditions (96 trials)
3 replications of the complete design (72 trials)

This will result in a total of 504 trials per day.

Figure Captions

Figure 1. A schematic representation of events in experiment 1. Figure 1a presents the timing of events in the single task Sternberg condition. Figure 1b illustrates the single task running memory sequence of events. The dual task conditions are presented in figure 1c. For each of the sequences, "digit" refers to a running memory trial and "probe" refers to a Sternberg trial. Time runs across the horizontal axis.

Figure 2 The mean reaction time POC curves obtained in experiment 1. The top two panels of figure 2 present the reaction time means for CM conditions, the bottom two panels illustrate VM conditions. The left panels represent target/match trials and the right panels represent non-target/mismatch trials. Within each panel, Sternberg performance is cross-plotted with running memory performance. The squares represent memory set size 1, the triangles represent memory set size 4. The numbers within each geometric shape refer to the condition in the experiment. 1 = single task running memory; 2 = 100% running memory, 0% Sternberg; 3 = 90% running memory, 10% Sternberg; 4 = 50% running memory, 50% Sternberg; 5 = 10% running memory, 90% Sternberg; 6 = 0% running memory, 100% Sternberg; 7 = single task Sternberg. The solid and dashed lines are the least squares polynomial regression fits for memory set sizes 1 and 4 respectively. For conditions without matching observations (e.g., single task and 100% conditions) the least squares estimate was used.

Figure 3. The A' POC curves for CM and VM conditions in experiment 1. The data within each panel are arranged in identical order with figure 2.

Figure 4. The grandaverage Pz overplots for CM and VM conditions as a function of priority for the Sternberg and running memory tasks. ERPs are plotted for the memory set size 4, target/match dual task conditions.

Figure 4a presents the unadjusted superaverages and figure 4b presents the latency adjusted waveforms. In each figure, four panels are presented. The left two panels present the ERPS elicited by the Sternberg probes, the right panels present the ERPs elicited by the running memory stimuli. The top panels present CM conditions, the bottom panels present VM conditions.

Figure 5. The P300 amplitude POC curves for experiment 1. The data are organized in the same format as figure 2.

Figure 6. The P300 latency POC curves for experiment 1. The data are organized in the same format as figure 2.

Figure 7. The RT/P300 ratio POC curves for experiment 1. The data are presented in the same format as figure 2.

Figure 8. A schematic representation of the dual task structure in experiment 2. The pursuit step-tracking task was performed with the right hand. Subjects responded in the Sternberg task with their left hand.

Figure 9. The temporal sequence of events in the dual task (9a), single task Sternberg (9b), and single task step-tracking (9c) conditions in experiment 2. Time runs along the horizontal axis.

Figure 10. Mean reaction time for the different Sternberg conditions in experiment 2. Single task Sternberg means are presented in the top two panels (10a). Dual task, first-order tracking Sternberg means are presented in the middle two panels (10b). The dual task, second-order tracking Sternberg means are presented in the bottom two panels (10c). Consistent mapping conditions are presented in the left hand panels; varied mapping conditions are presented on the right. Within each panel mean RT is plotted as a function of memory set size, response type, and session.

Figure 11. Figure 11a presents the mean reaction time for non-targets, targets presented in the left position in the display, and targets presented

in the right position in the display. The left hand portion of the figure presents CM conditions, the right presents VM conditions. Figure 11b presents the mean P300 latency, plotted in the same format as figure 11a.

Figure 12. Mean error rate for all Sternberg conditions in experiment 2. The data are arranged in the same format as figure 10.

Figure 13. Superaverage Pz ERP waveforms for each Sternberg condition in experiment 2. Memory set sizes 2, 3, and 4 are overplotted.

Figure 14. Mean P300 latency for all Sternberg conditions in experiment 2. The data are presented in the same format as figure 10.

Figure 15. Mean RT/P300 ratio for all Sternberg conditions in experiment 2. The data are presented in the same format as figure 10. In each panel, a horizontal line is drawn at a RT/P300 ratio of 1.0, which indicates the point at which RT and the P300 peak latency co-occur. Values below the line represent conditions where RT preceded P300 peak latency. Values above the line represent conditions where RT followed P300 peak latency.

Figure 16. Mean reaction time for each condition in experiment 3a. The top panel presents target trials, the bottom panel presents non-target trials. The data are plotted as a function of memory set size for each delay and SOA condition. The left column in the figure presents the 200 msec SOA condition, the center column presents the 500 msec SOA condition, and the right column represents the 1000 msec SOA condition. The memory set size slopes for each condition are indicated to the right of each condition. The mean difference between delay conditions is also indicated in the figure.

Figure 17. The vincentized cumulative frequency distributions for the 0 and 15 second delay conditions at each SOA condition. The target memory load 4 condition is presented. The reaction time distribution was divided into 5% quantiles and the mean latency of each quantile was calculated. The means

are plotted as a function of quantile.

Figure 18. An examination of different mixtures of primary and secondary memory. The data are presented as vincentized CFDs. The solid line represents the 0 second delay, 200 msec SOA condition, the dashed line represents the 15 second delay, 200 msec SOA condition. The dotted line presents the data obtained in the 15 second delay, 1000 SOA condition (adjusted for the main effect of SOA). Three mixture conditions are presented which represent 25/75, 50/50, and 75/25 mixtures of primary and secondary memory. It is apparent that the data obtained in the 15 second delay, 1000 msec SOA condition falls between the 50/50 and 25/75 mixture conditions.

Figure 19. Hypothetical outcomes from experiment 3b. The figure is organized into 5 rows, each with two panels. The left panel represents the 200 msec SOA condition, the right panel presents the 1000 msec SOA condition. Within each panel hypothetical mean reaction time values are presented as a function of set size for the 0, 4, and 15 second delay conditions. The first row of the figure presents the VM control data. The second row presents the hypothetical outcome of the CM condition if no reduction in retrieval time is obtained. The third row presents the hypothetical outcome of the CM condition if there is a partial reduction in retrieval time. The fourth row presents the hypothetical outcome where there is an partial reduction at the 200 msec SOA condition, and a full reduction at the 1000 msec SOA condition. The fifth row presents the hypothetical outcome where there is a full reduction in the retrieval time estimate following CM practice.

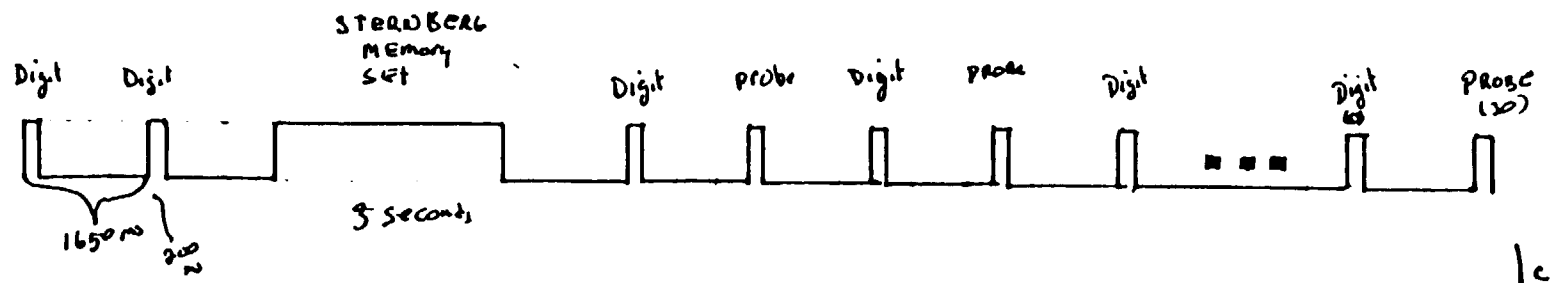
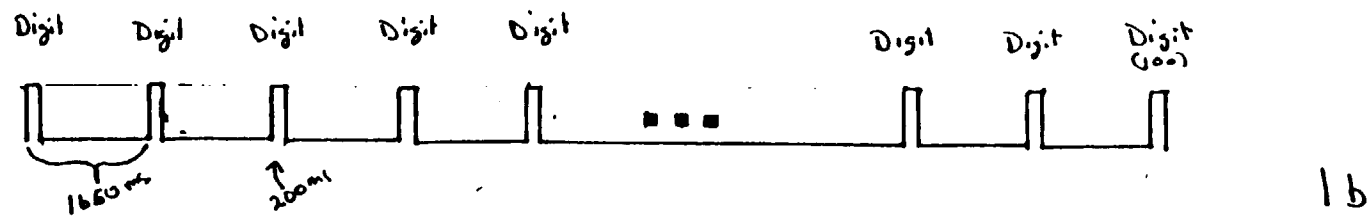
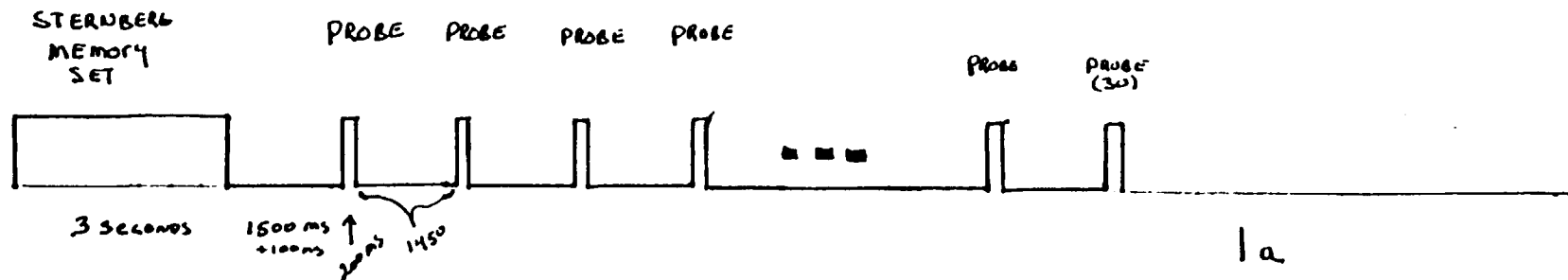


Figure 1

POSITIVE TRIALS

70

NEGATIVE TRIALS

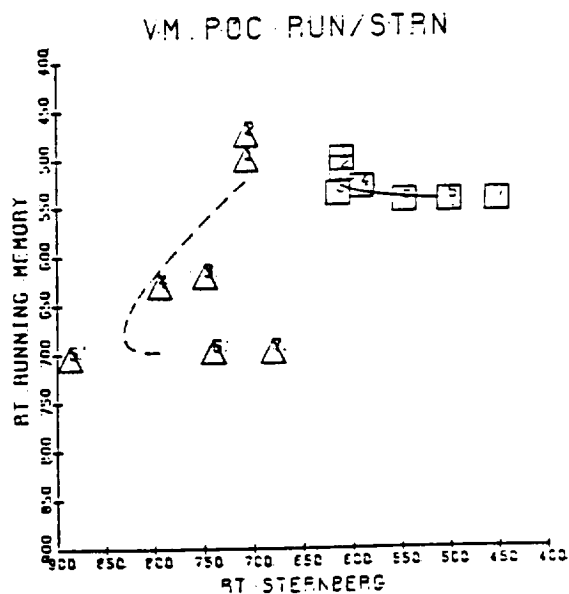
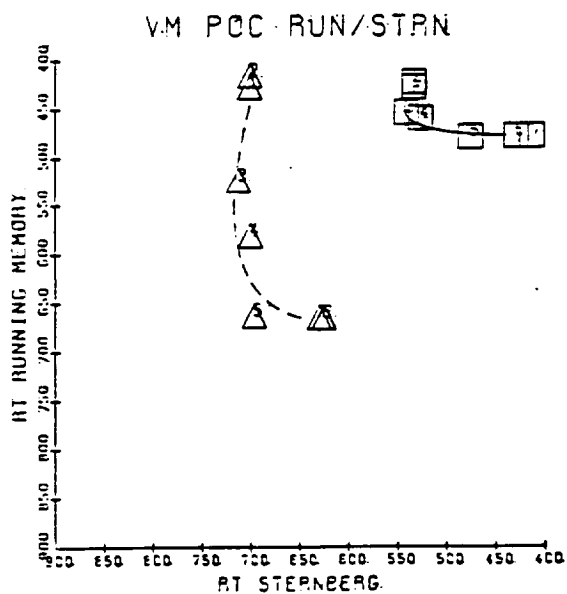
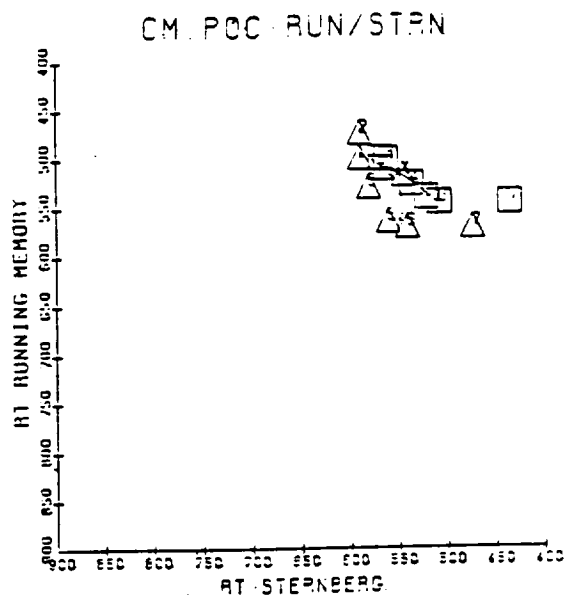
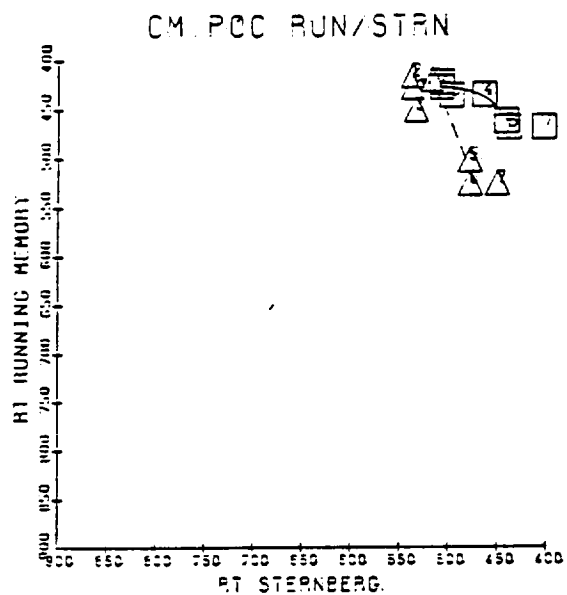


Figure 2

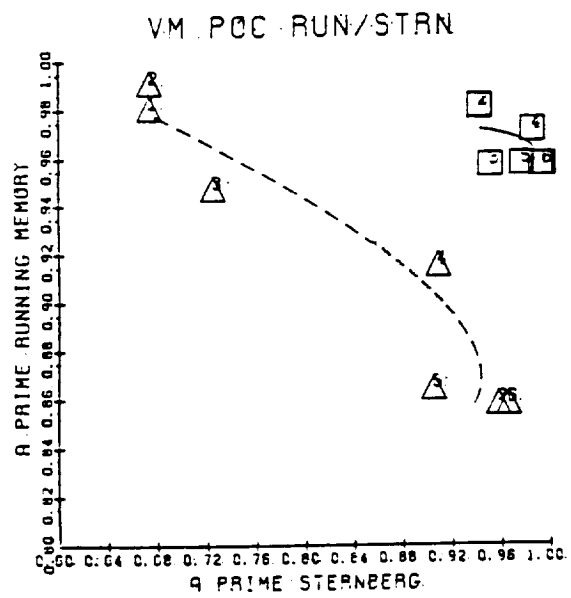
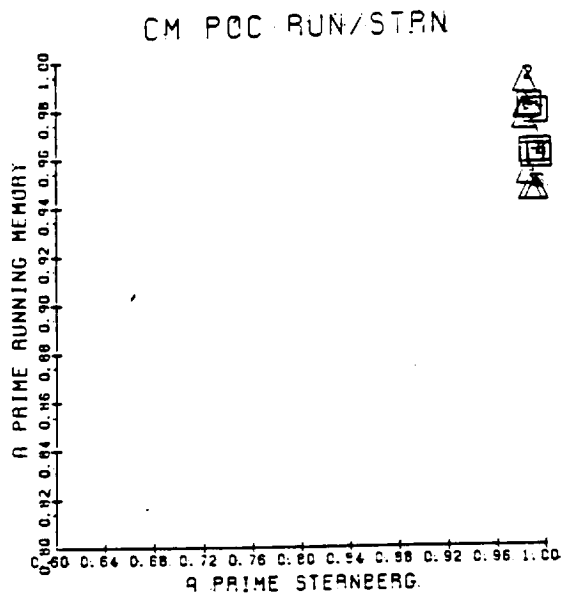
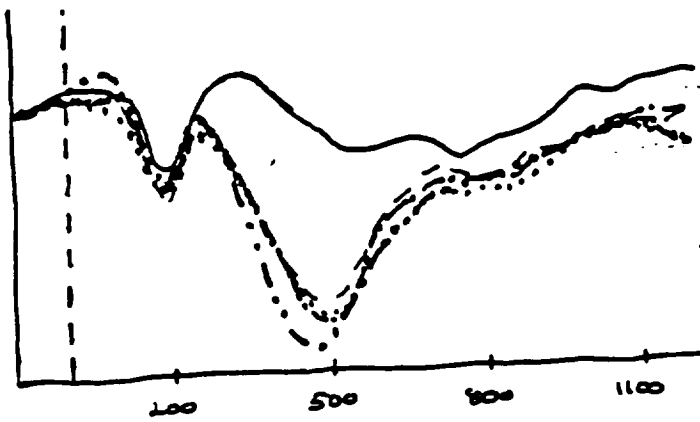


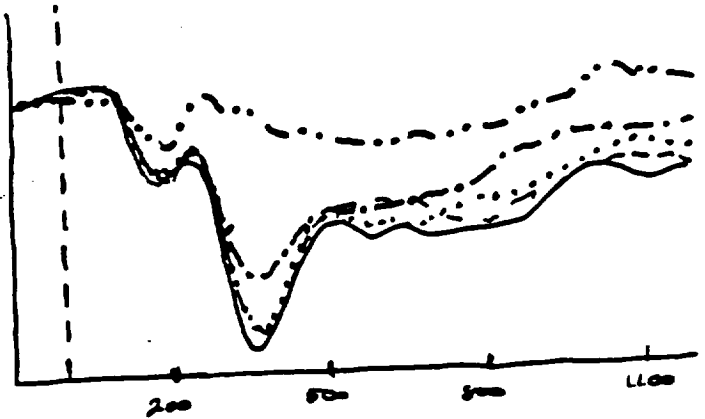
Figure 3

CM4

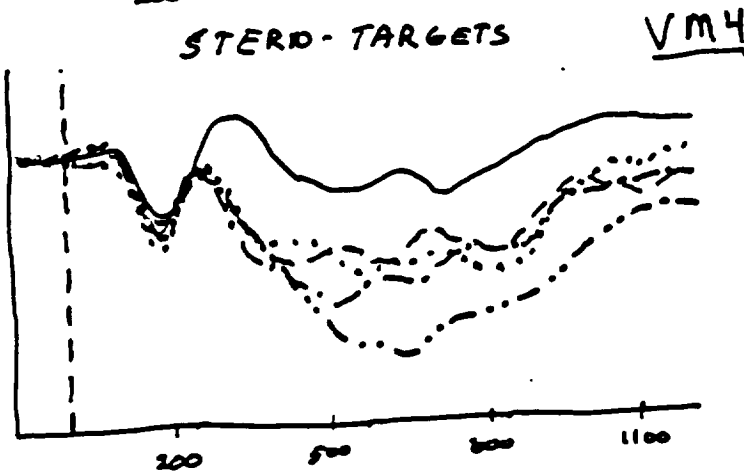
STEREO-TARGETS



RUN - MATCH

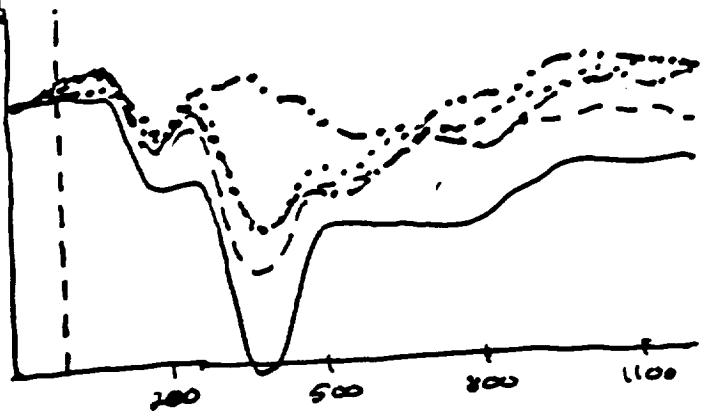


STEREO-TARGETS



VM4

RUN - MATCH



Run	STEREO
———— 100	0
----- 90	10
..... 50	50
-.-.-.- 10	90
..... 0	100

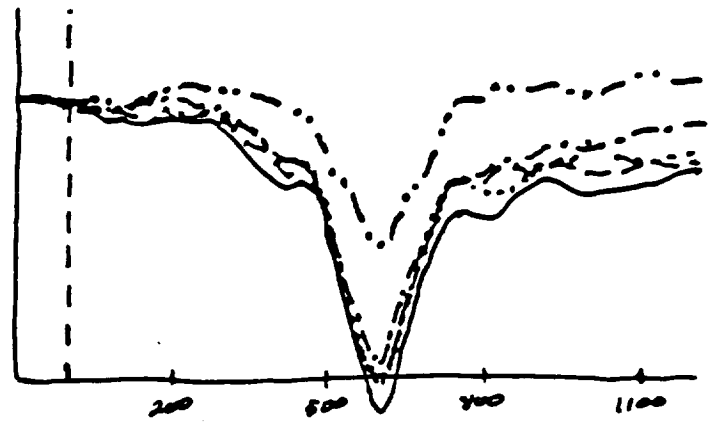
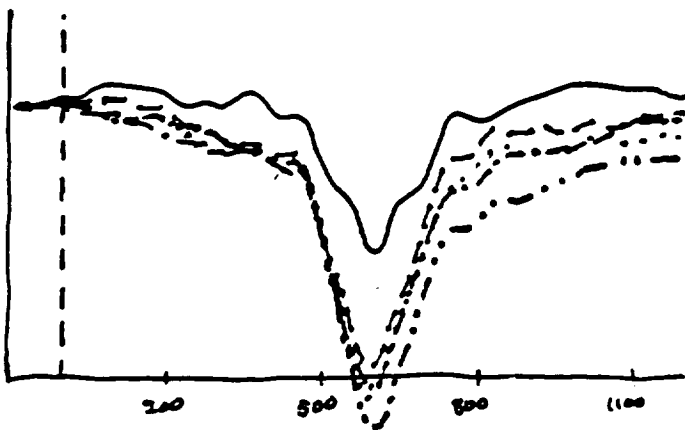
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Figure 4a

Stern-targets

CM 4

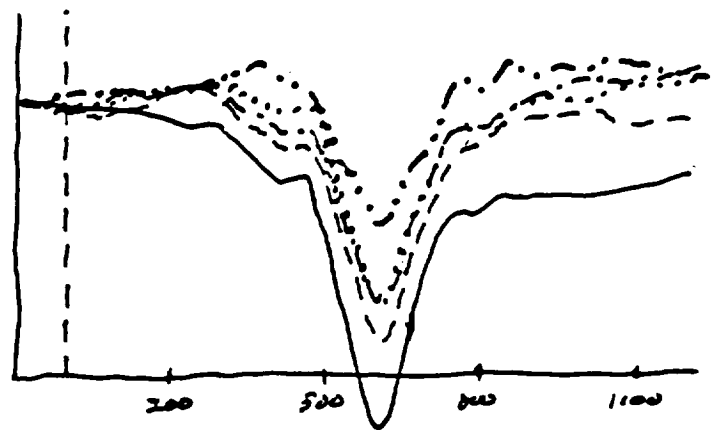
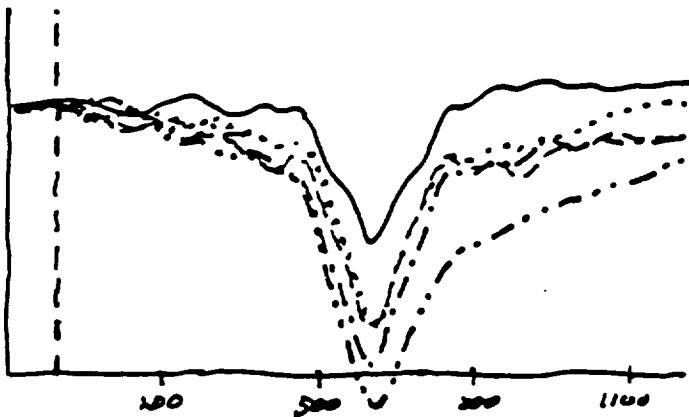
Run-match



STERN - targets

VM 4

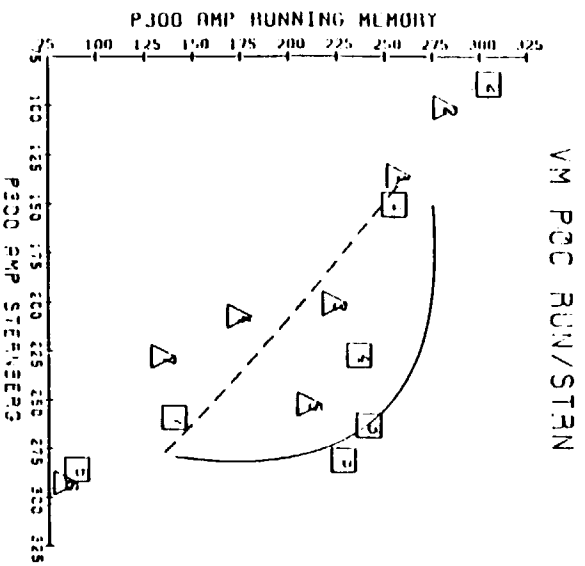
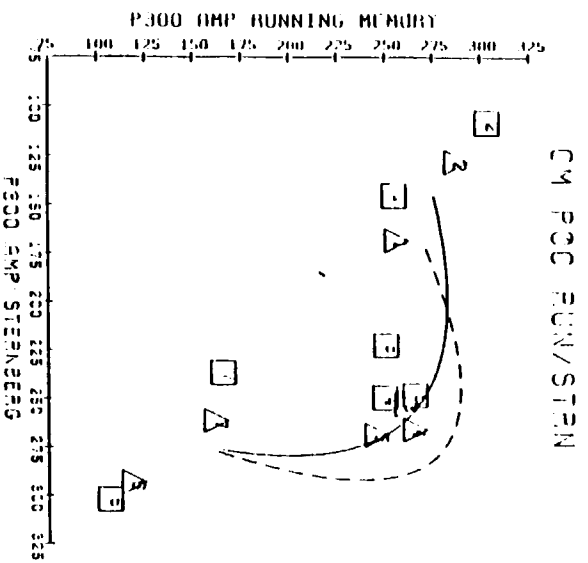
Run-match



	Run	STERN
————	100	0
-----	90	10
.....	50	60
-.-.-.-	10	90
..-.-.	0	100

LATENCY ADJUSTED

POSITIVE TRIALS



NEGATIVE TRIALS

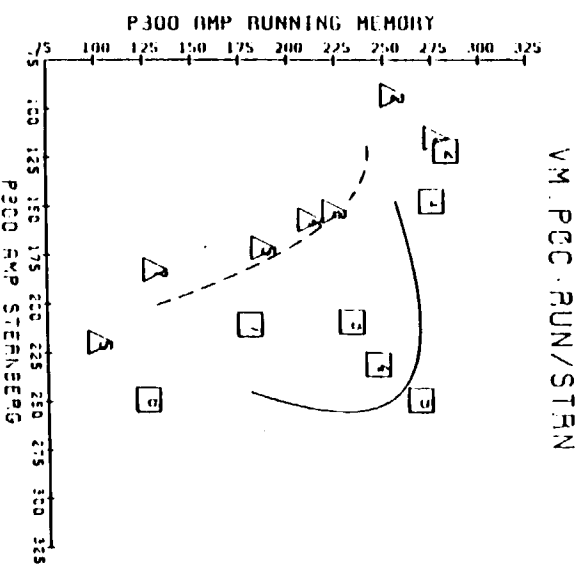
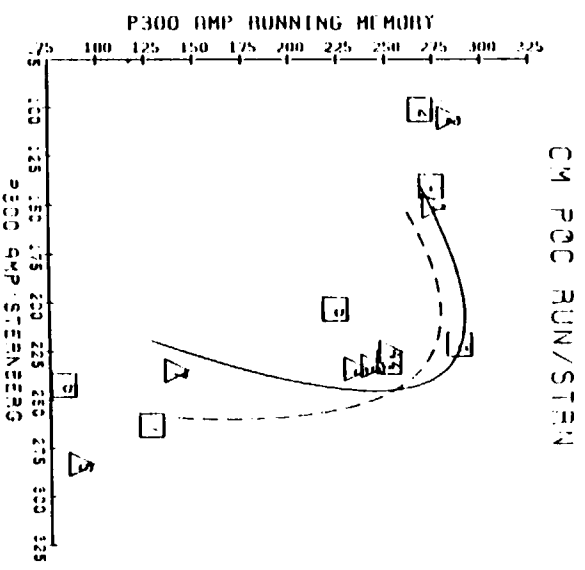
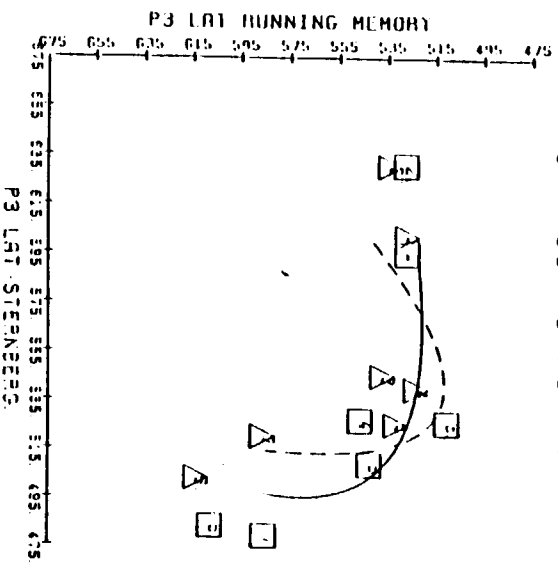


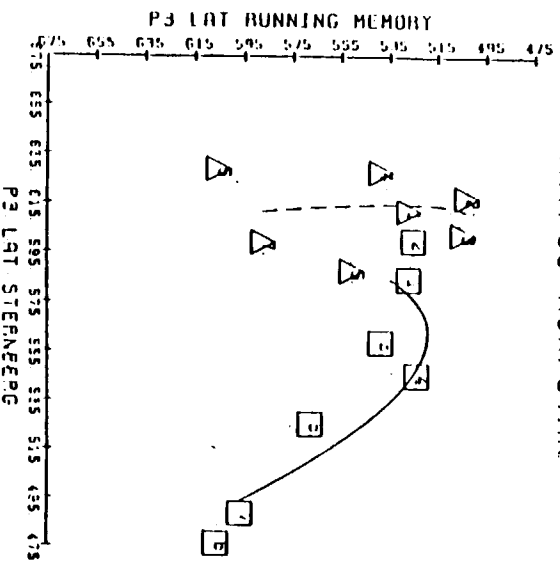
Figure 5

POSITIVE TRIALS

CM POC RUN/STAN

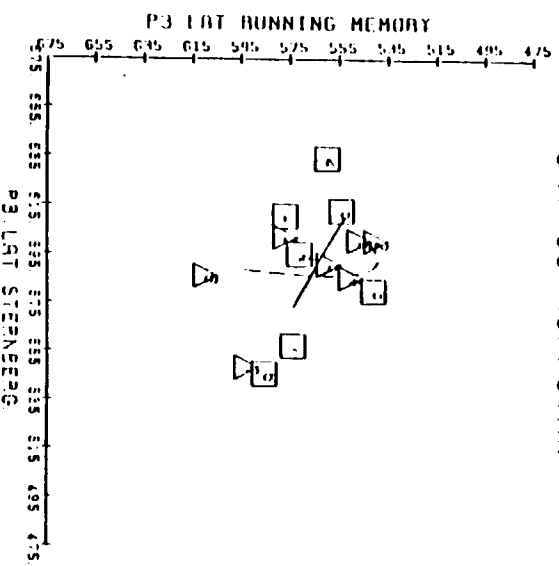


VM POC RUN/STAN



NEGATIVE TRIALS

CM POC RUN/STAN



VM POC RUN/STAN

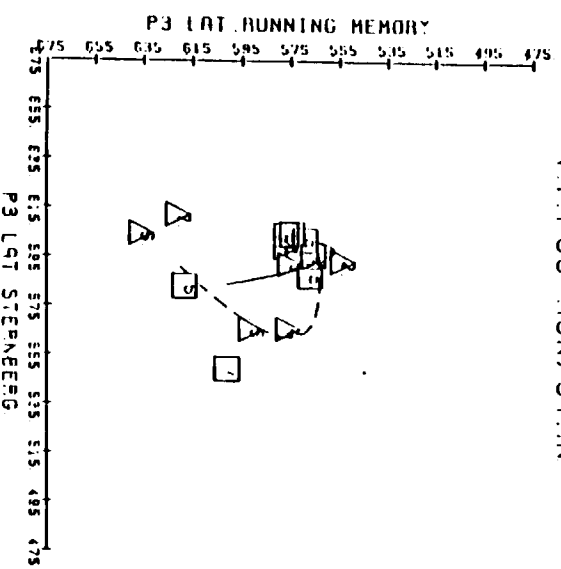
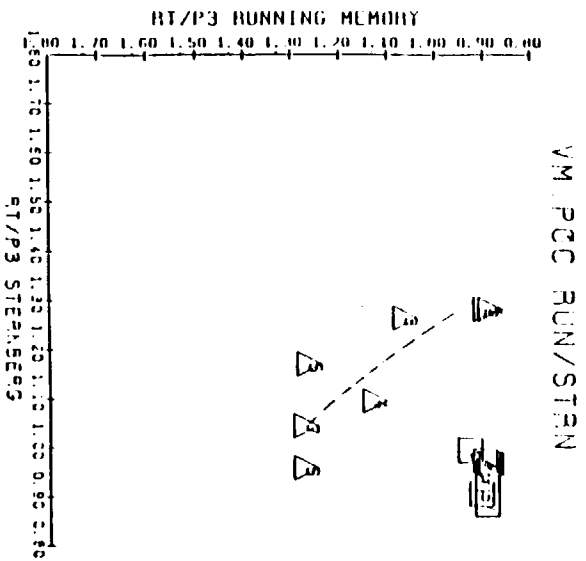
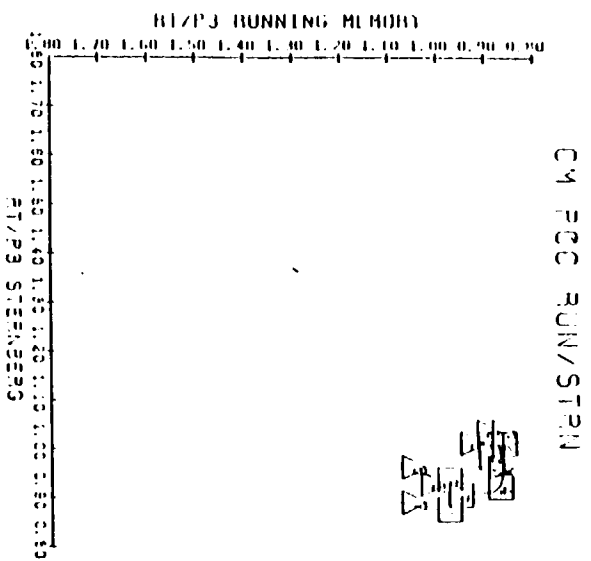


Figure 6

POSITIVE TRIALS



NEGATIVE TRIALS

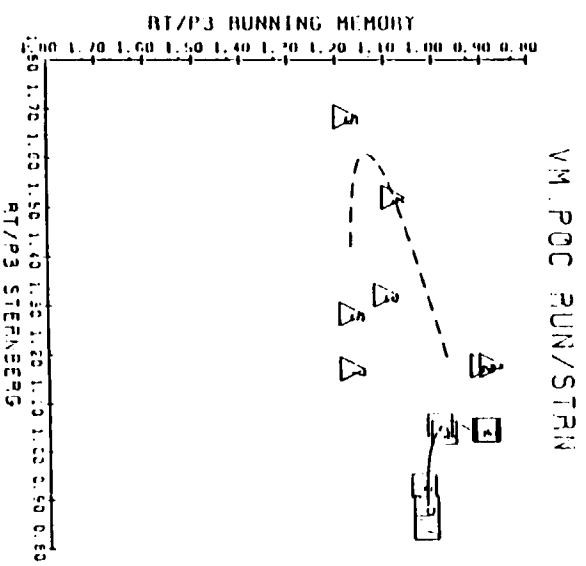
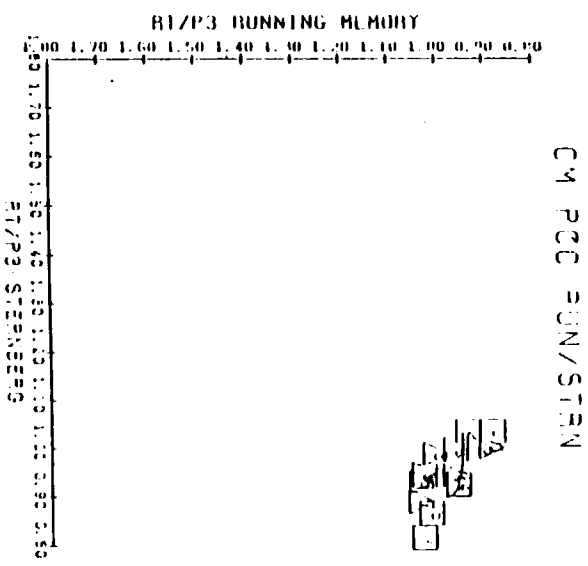


Figure 7

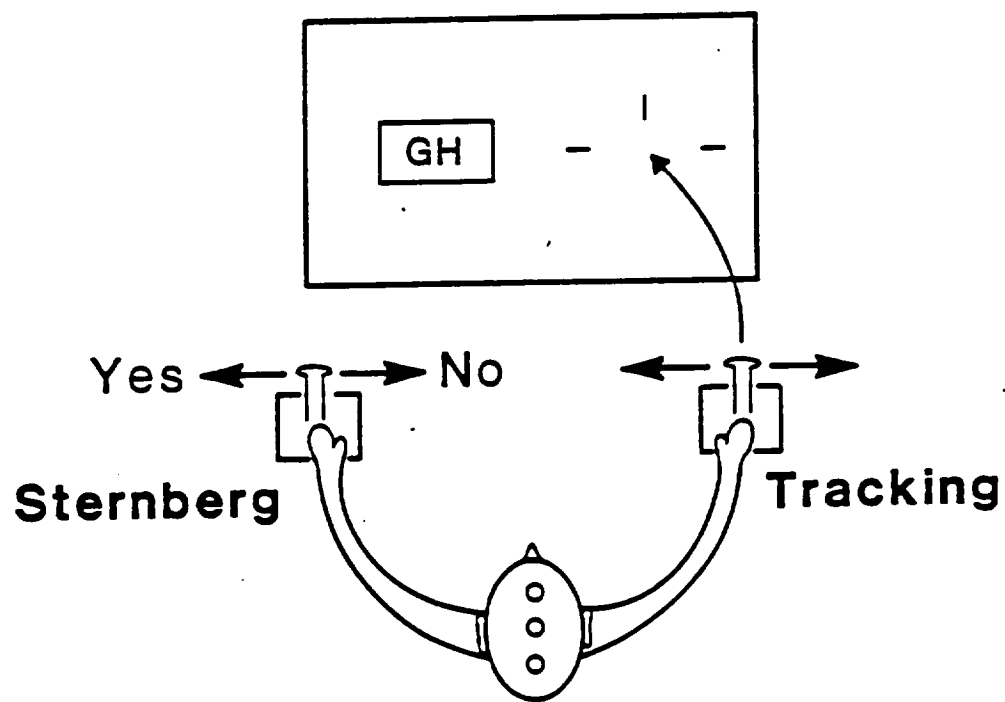
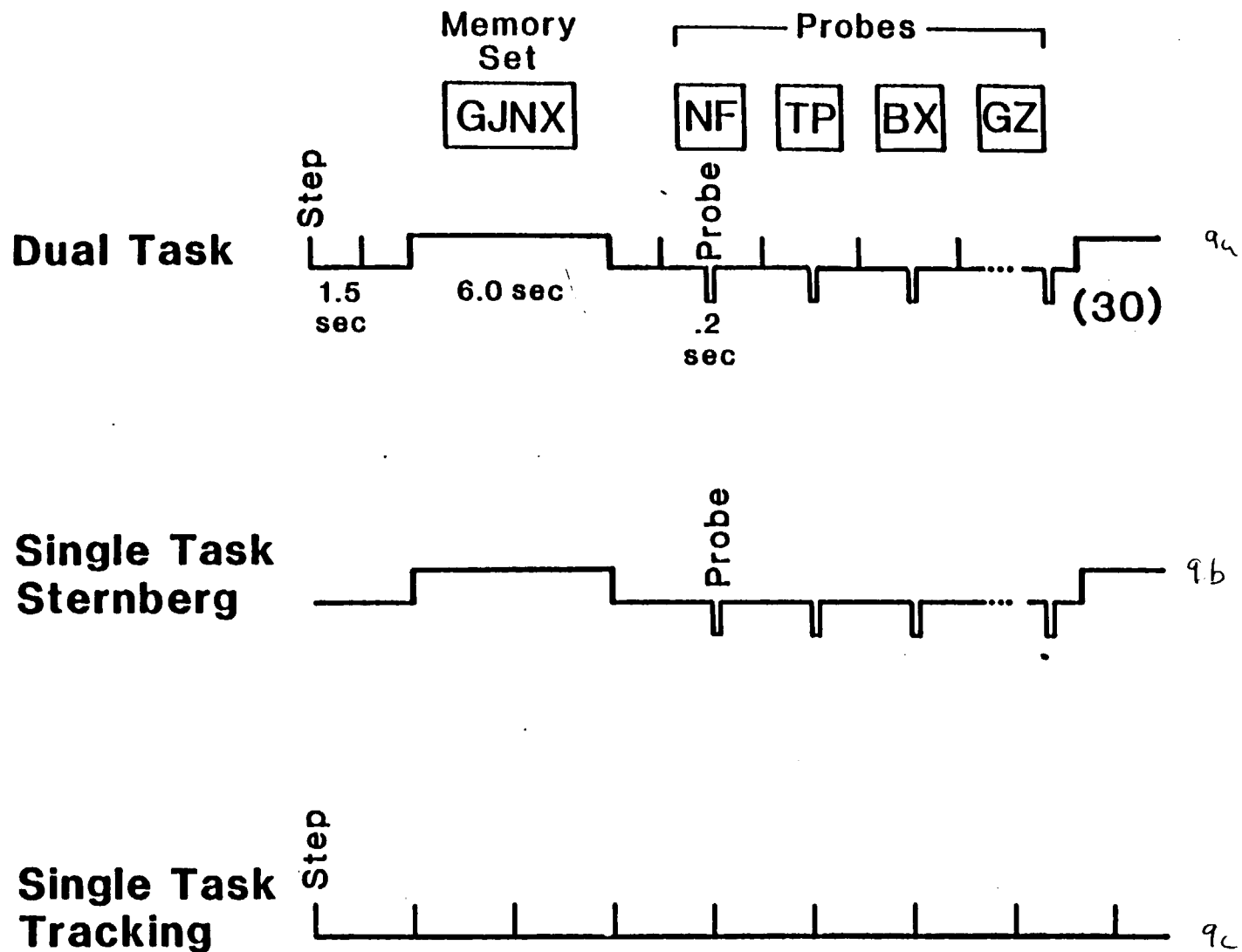


Figure 8



CM Targets: G J N X

VM Targets and Distractors

and CM Distractors: P H Z B F D V T

Figure 9

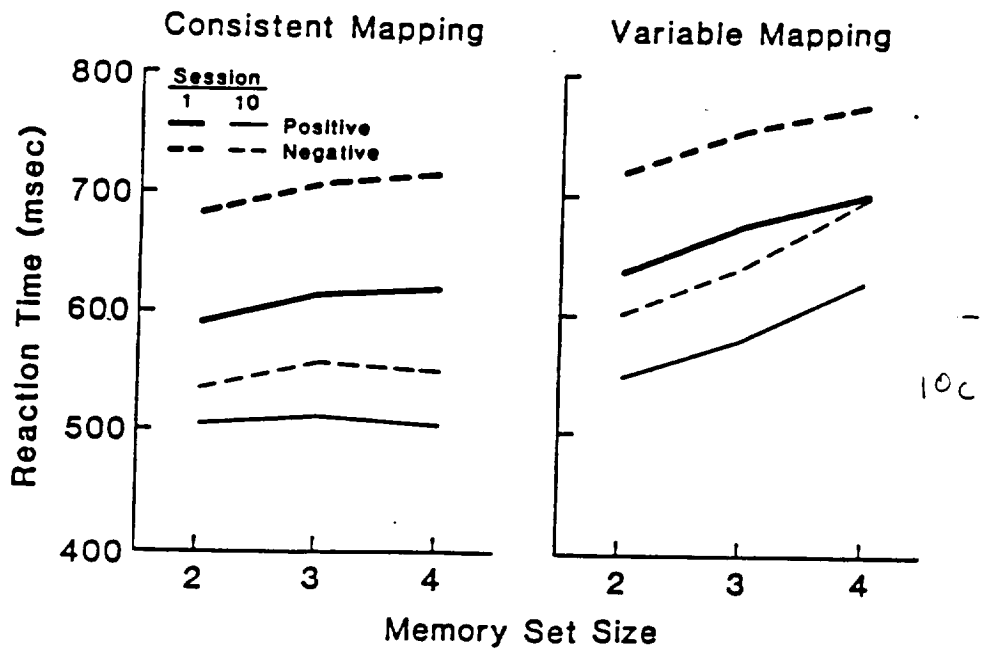
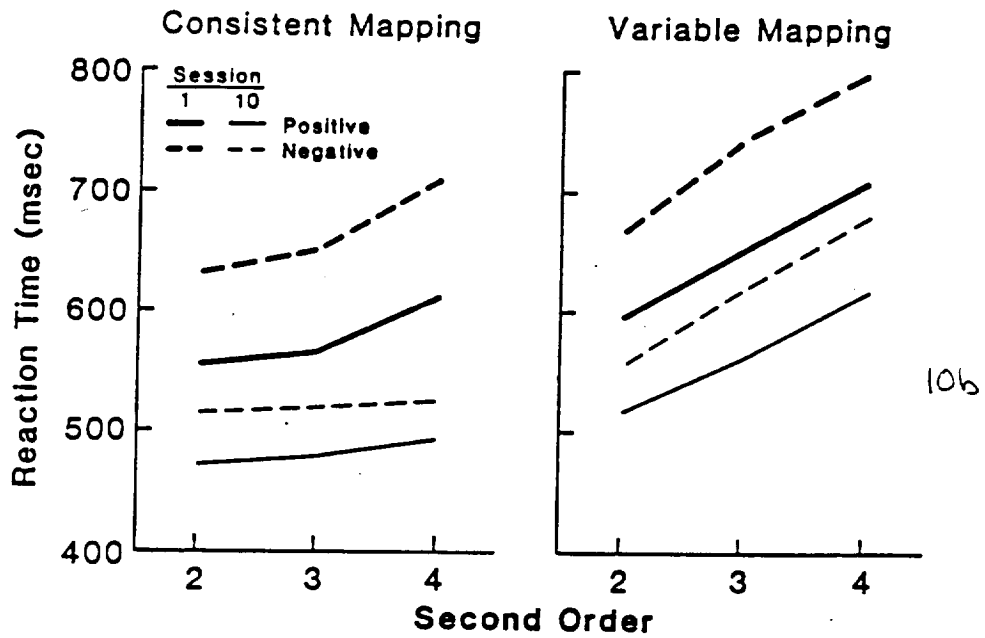
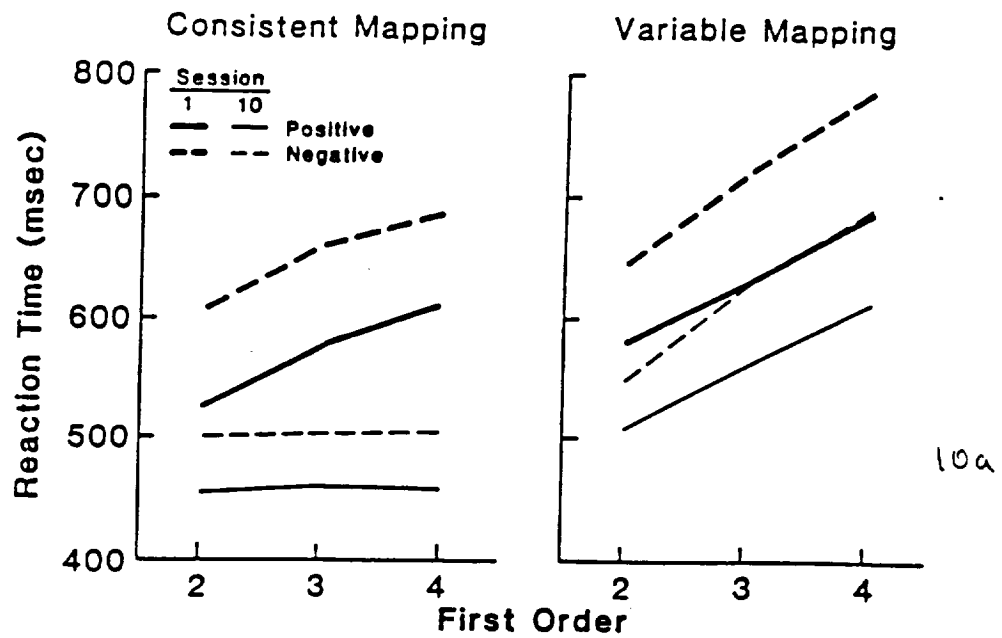
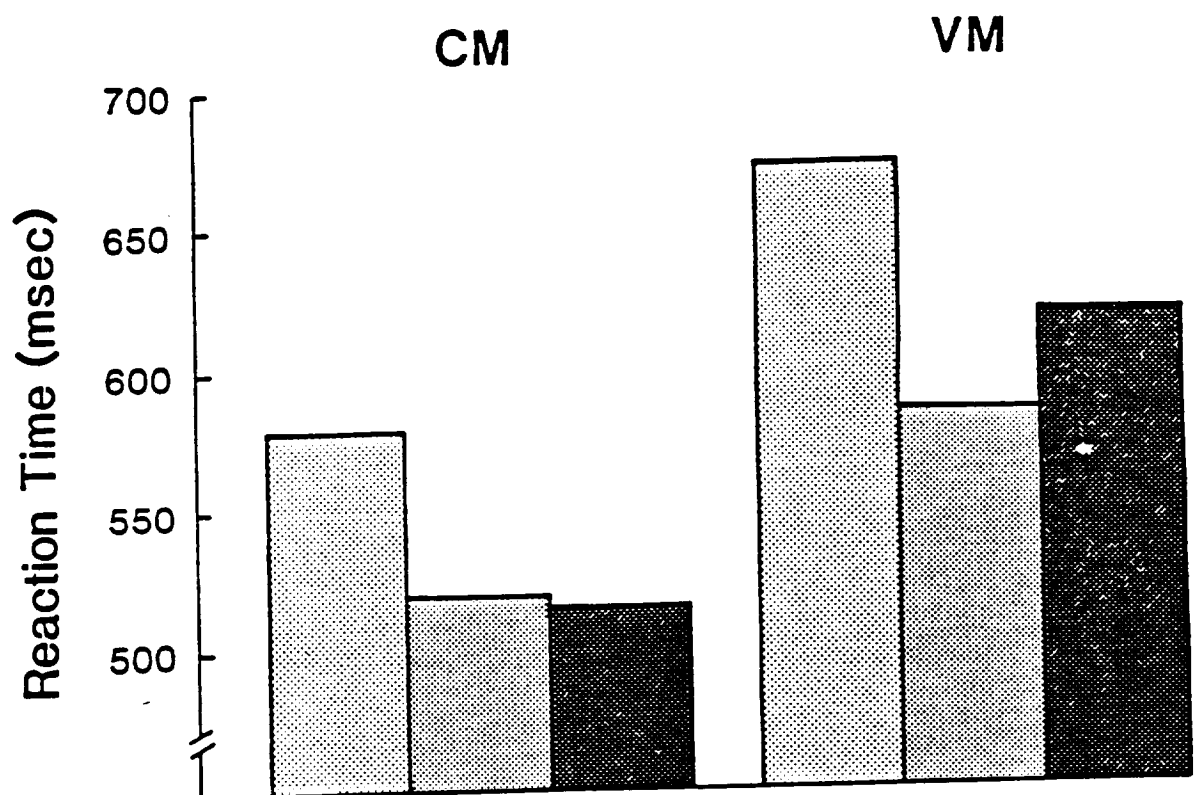
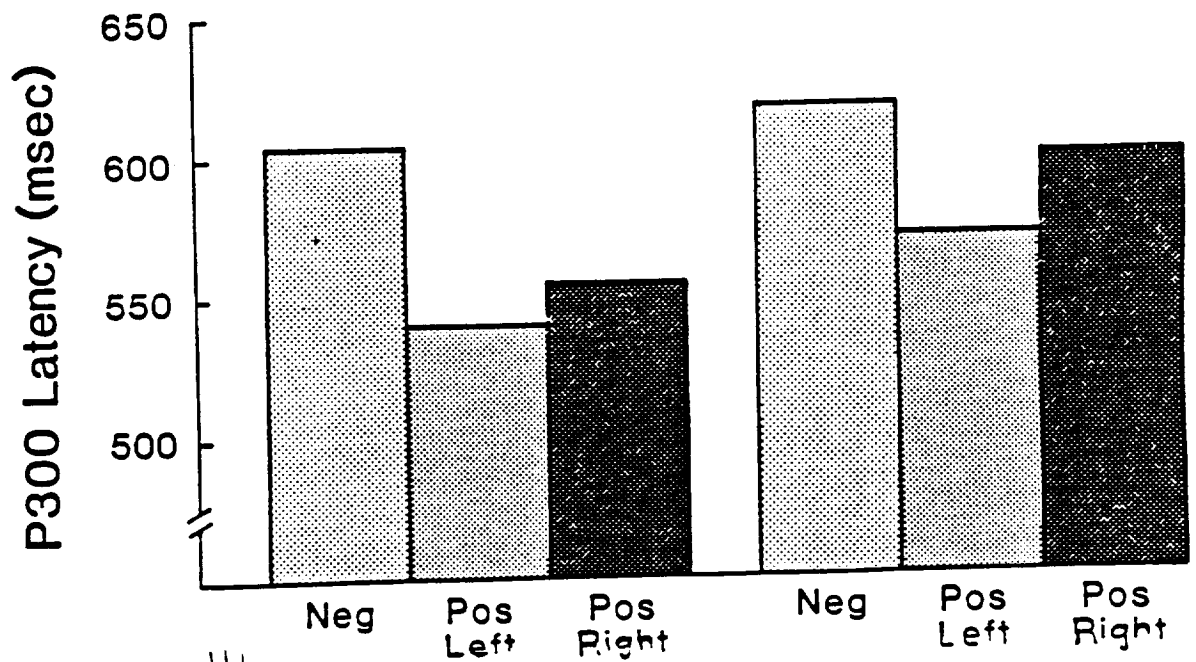


Figure 10



11a



11b

Single Task

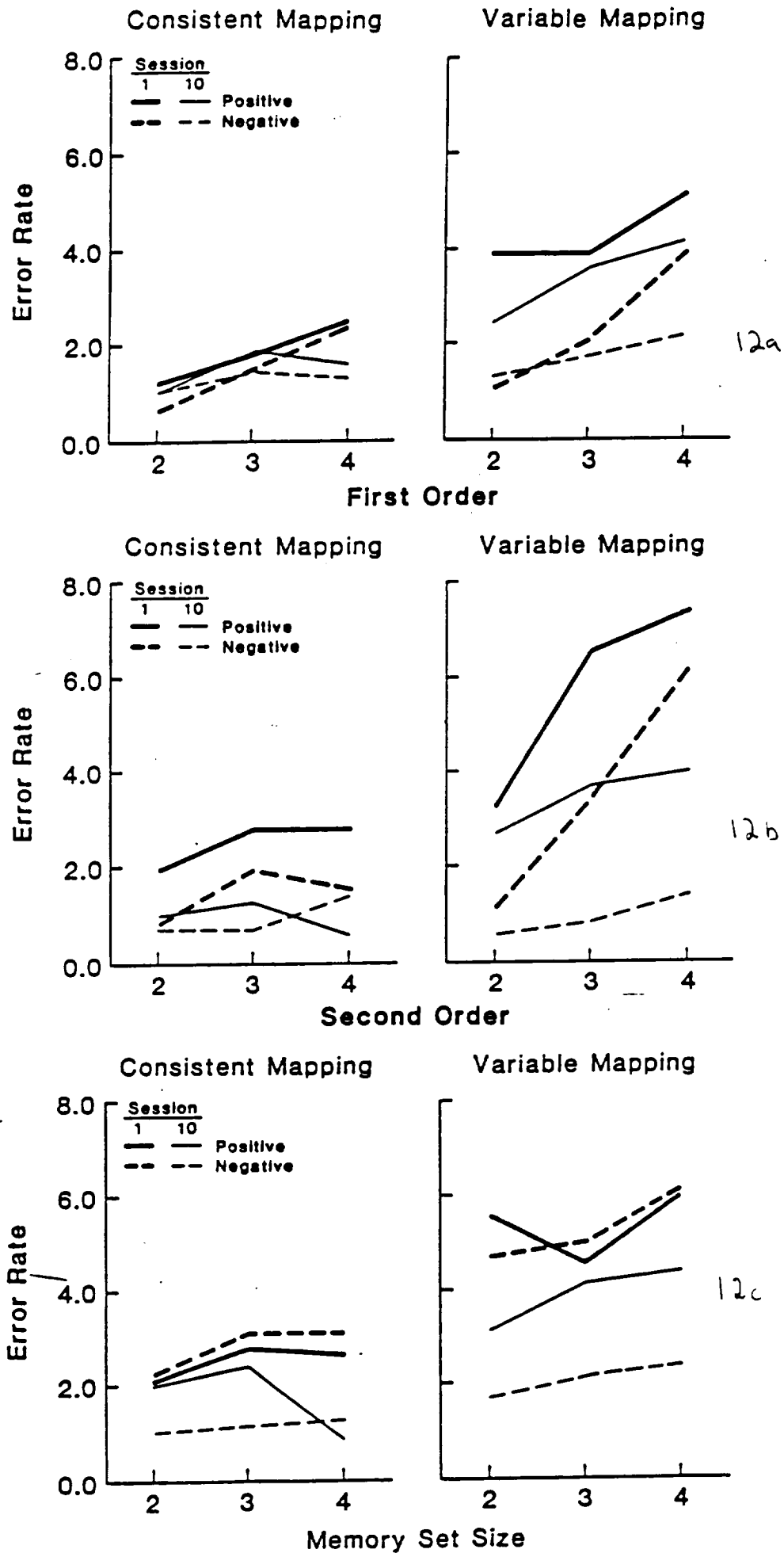


Figure 12

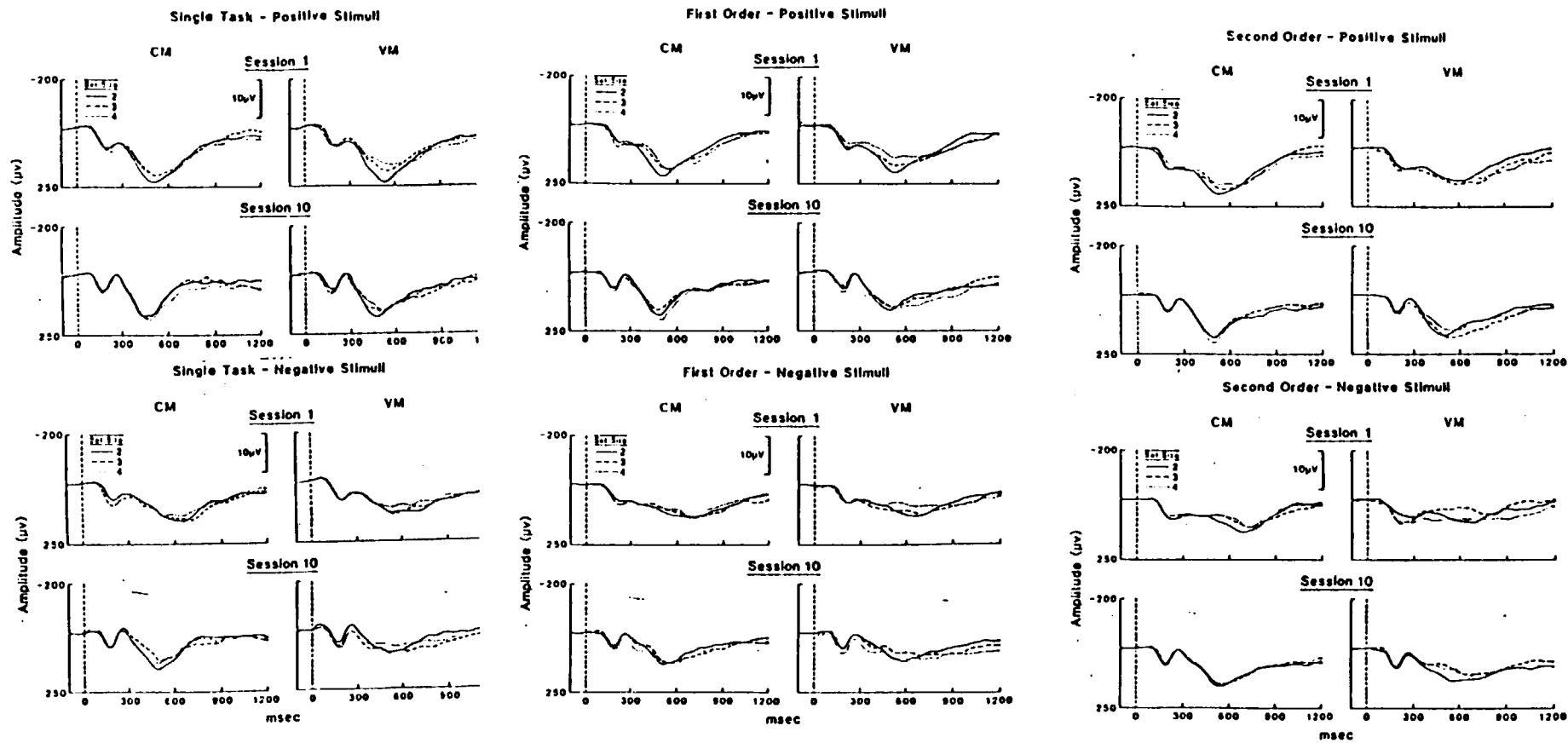


Figure 13

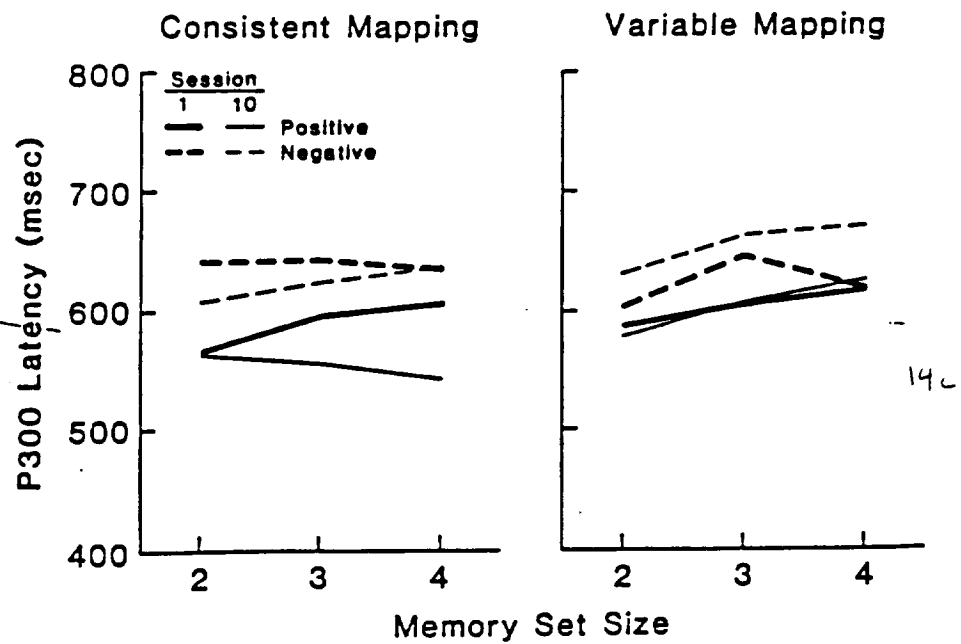
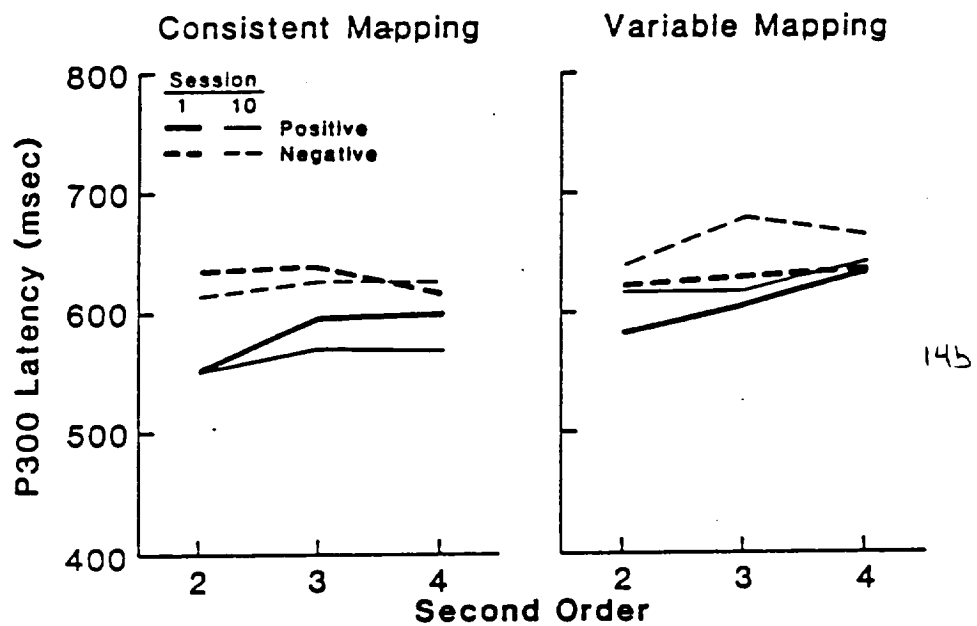
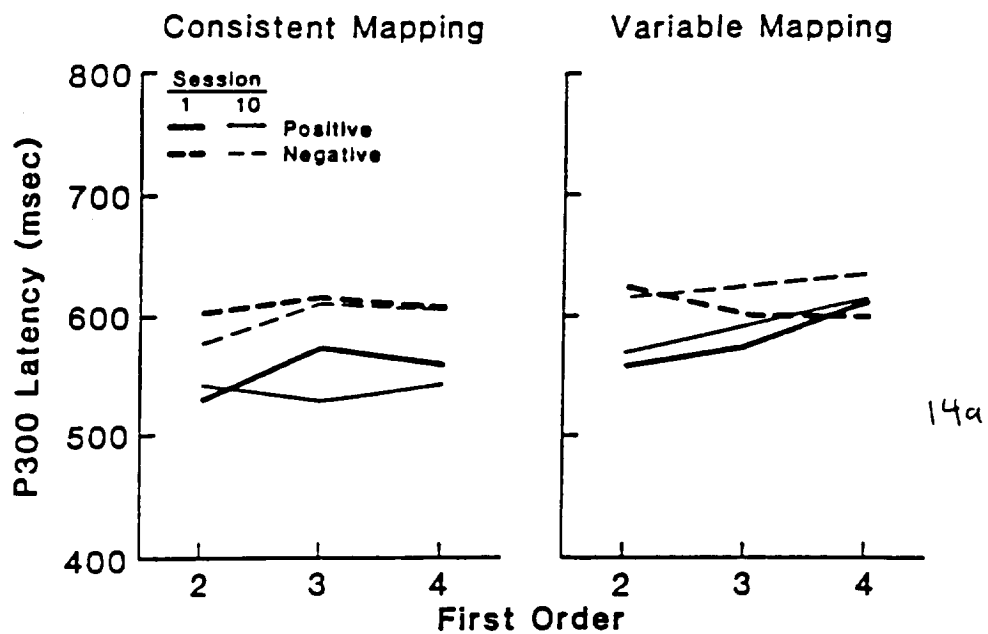


Figure 14

Single Task

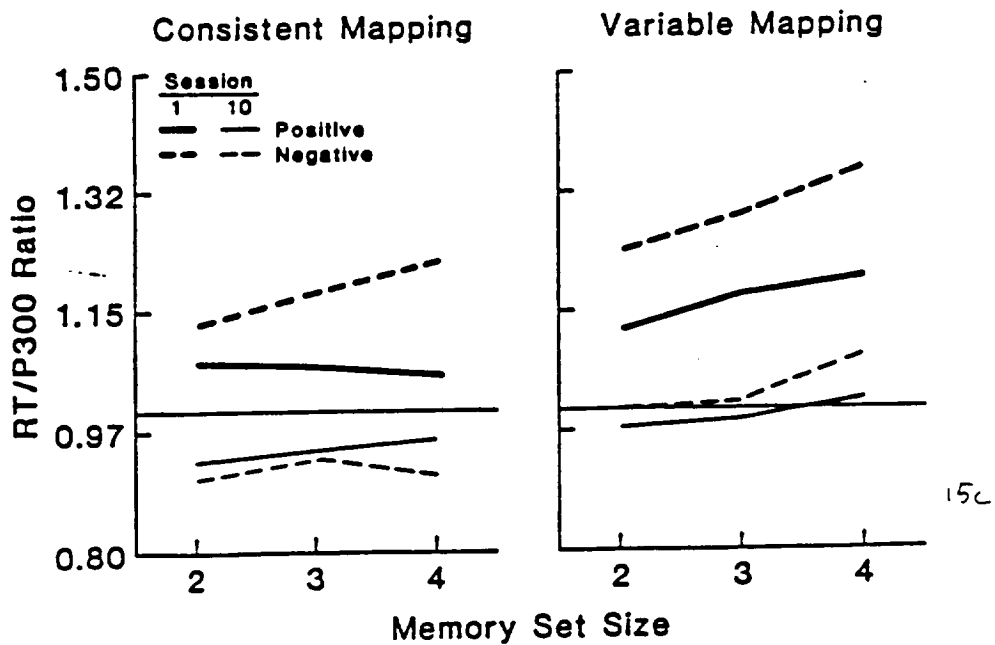
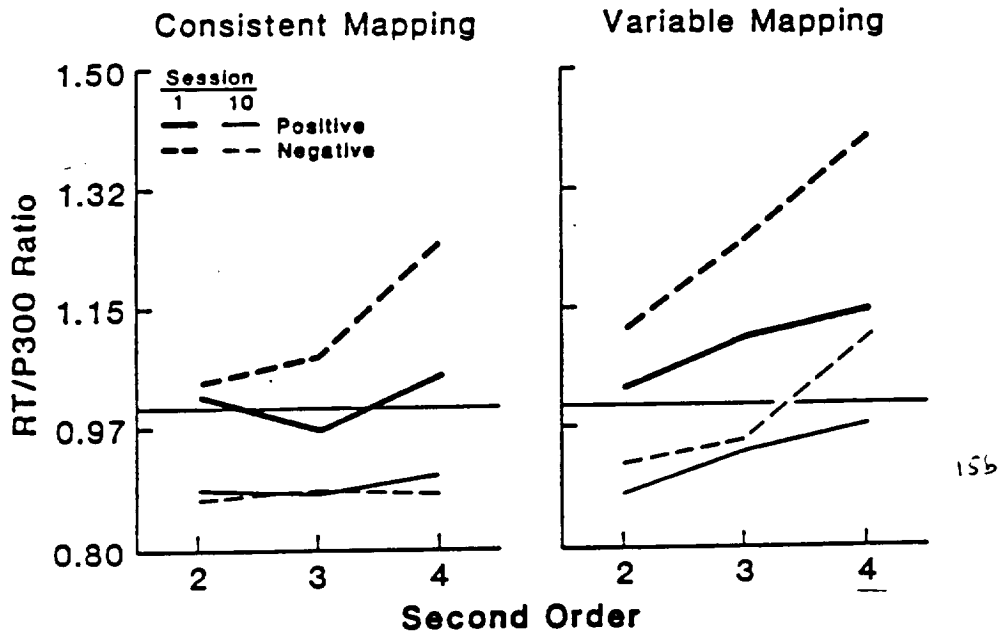
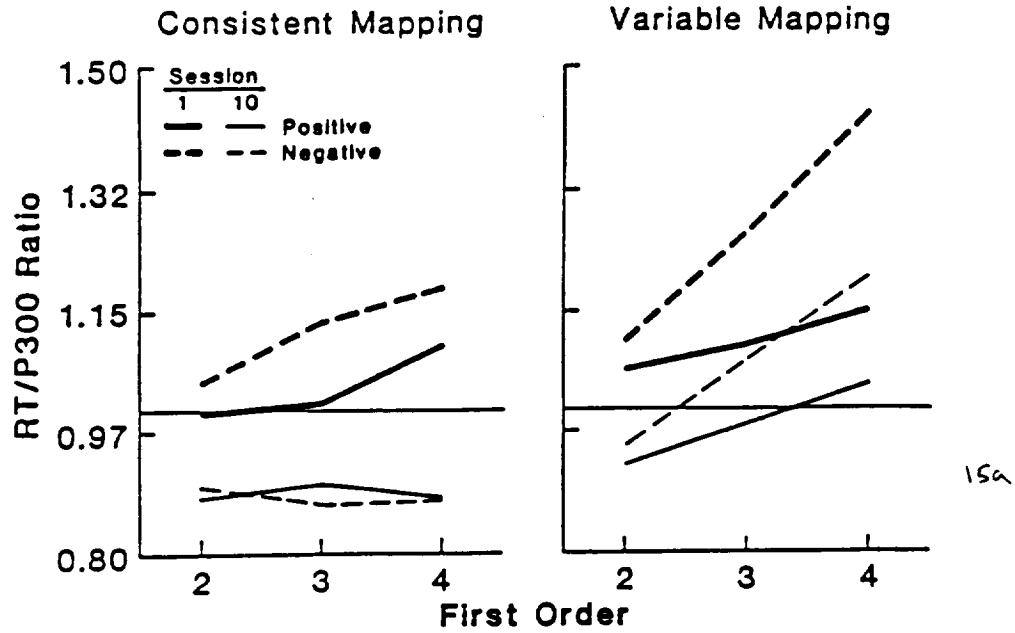


Figure 15

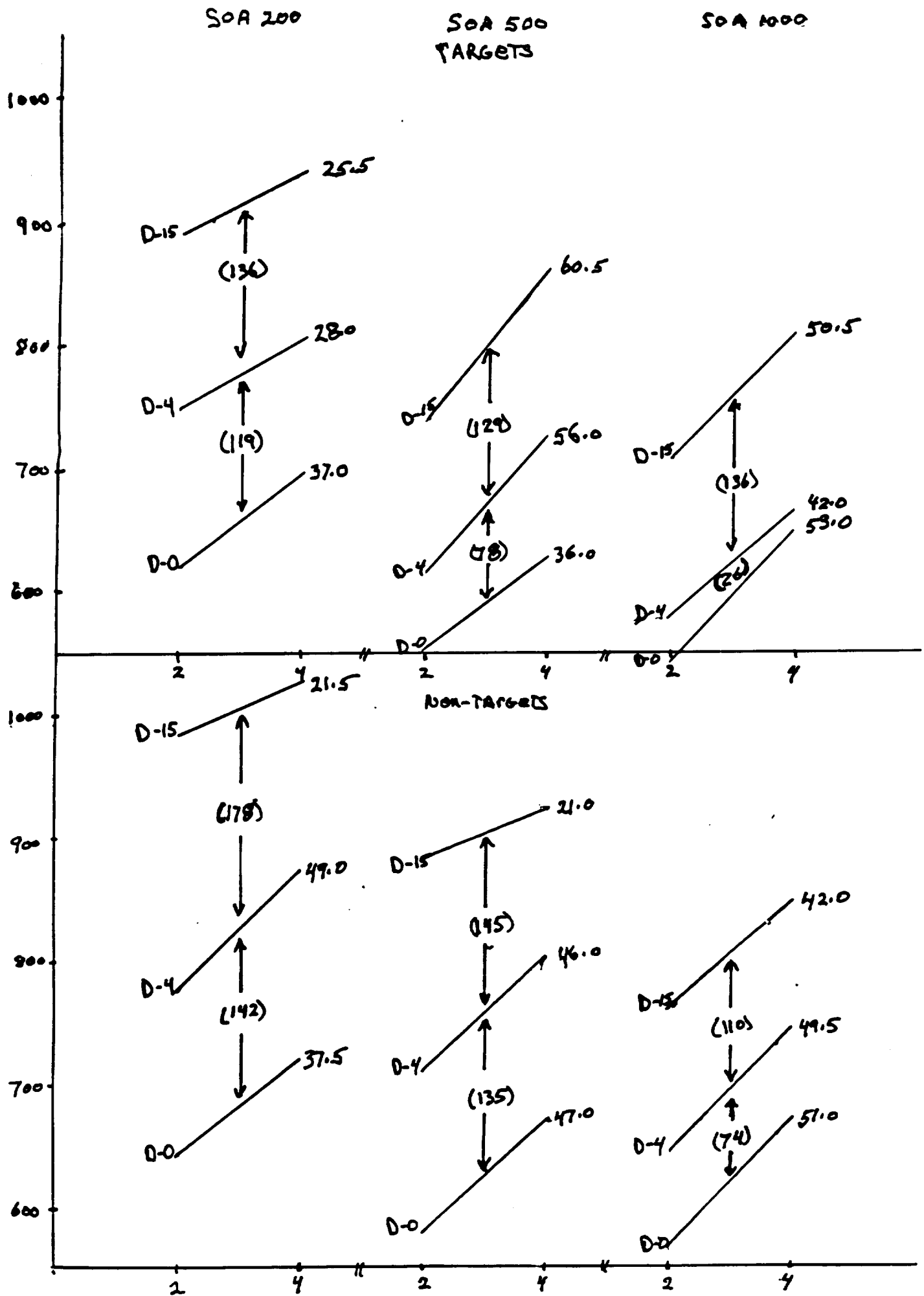
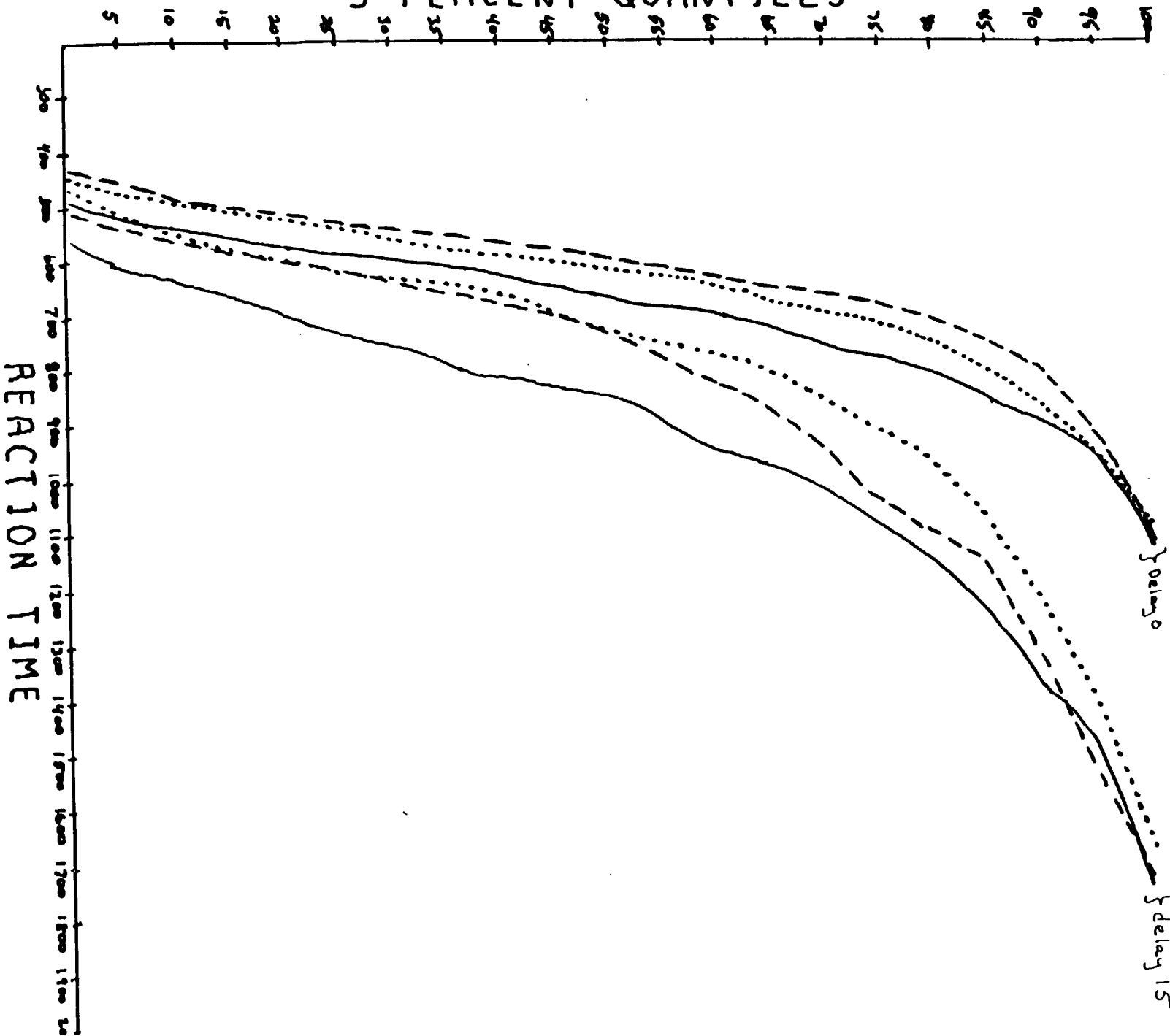


Figure 16

VINCENTIZED CFDS

5 PERCENT QUANTILES



TARGET LOAD 4

REACTION TIME

- Delay 0 500 200
- Delay 15 500 200
- Delay 30 500 500
- Delay 45 500 500
- Delay 60 500 1000

TARGET LOAD 4

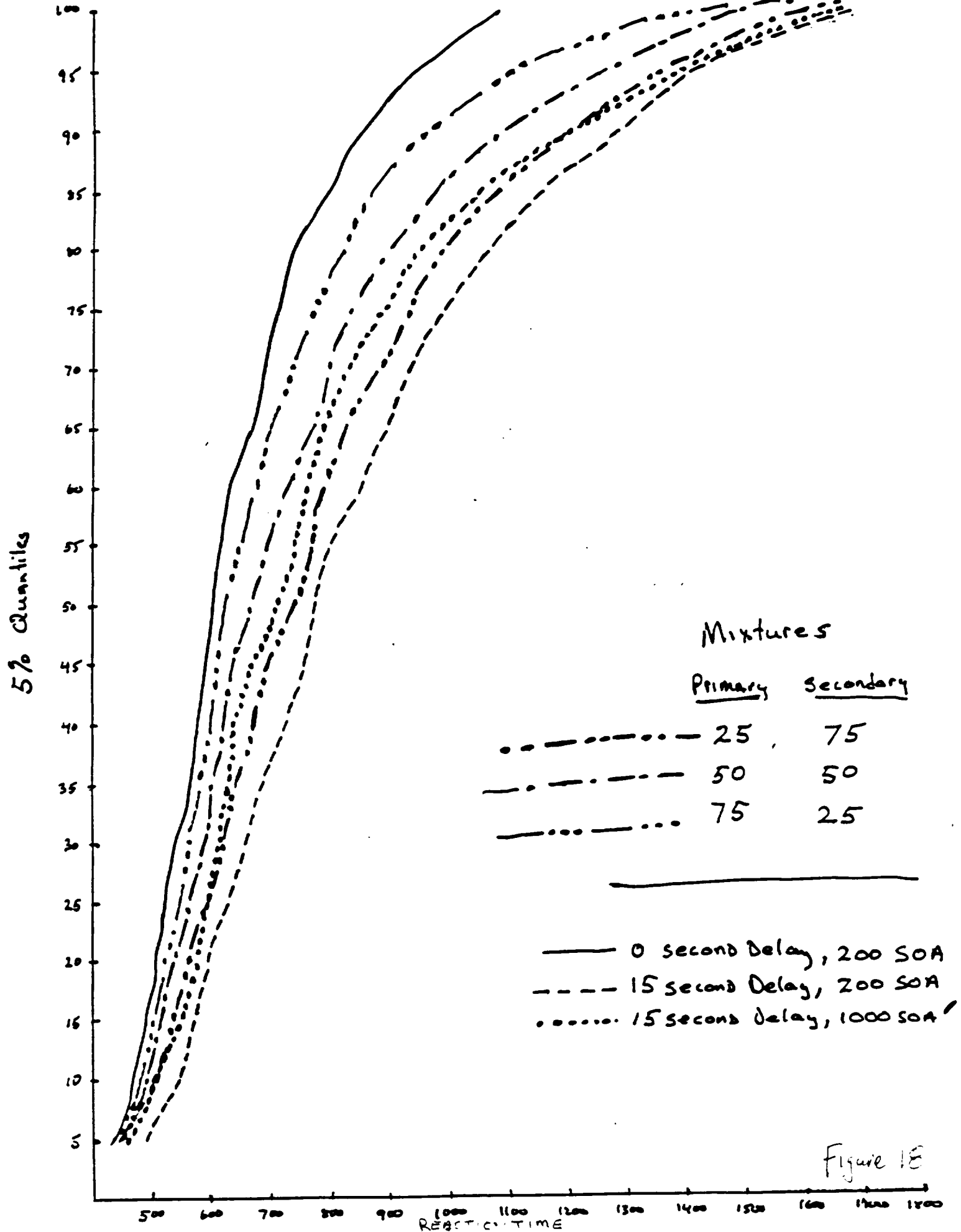
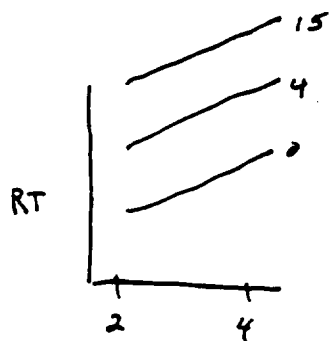


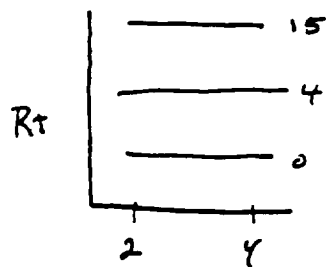
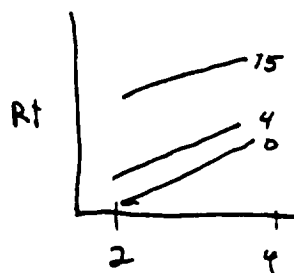
Figure 1E

SOA 200

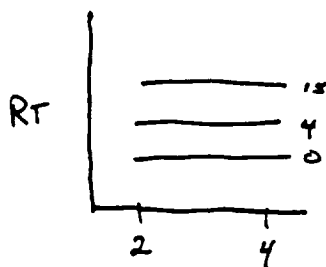
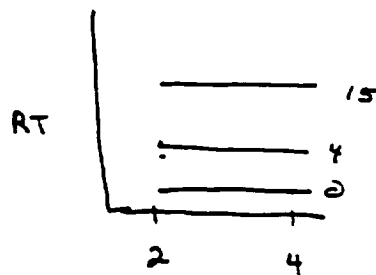


VM
CONTROL

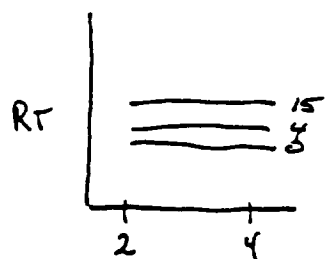
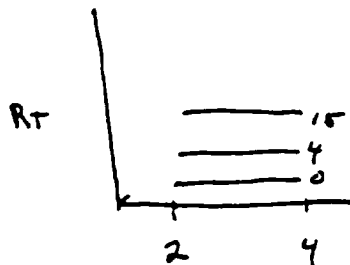
SOA 1000



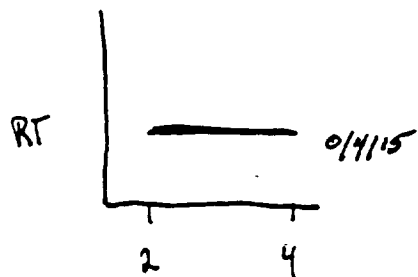
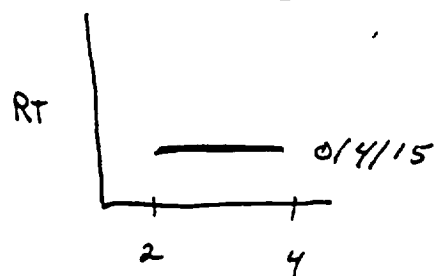
NO REDUCTION



PARTIAL
REDUCTION



PARTIAL REDUCTION
EARLY, Full Reduction
AT 1000 SOA



Full REDUCTION

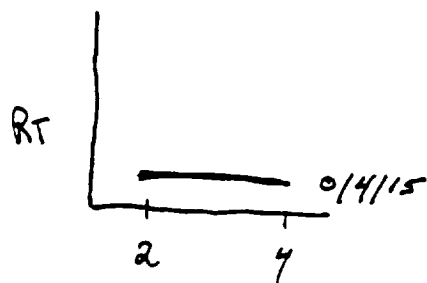


Figure 19

APPENDIX B: CURRICULUM VITAE